CRA

CONESTOGA-ROVERS & ASSOCIATES
1801 Old Highway 8, Suite 114
St. Paul, Minnesota 55112
(612) 639-0913 Fax (612) 639-0923

November 6, 1997 Reference No. 6711

Mr. Jerry Willman
ILLINOIS ENVIRONMENTAL PROTECTION AGENCY
2200 Churchill Road
Springfield, Illinois 62794-9276

Dear Mr. Willmar:

Re: Vacuum Enhanced Recovery
Lenz Oil Superfund Site

Per your request, please find enclosed technical papers on the VER technology. Please note that bioslurping is the same as VER.

We would like the opportunity to meet with USEPA and IEPA to present the technology.

Sincerely,

CONESTOGA-ROVERS & ASSOCIATES

R. Frehner

Ronald Frehner

RF/br
Enc.
c.c. **Mary Tierney**; USEPA (w/Enc.)
Alan Bielawski; Sidley & Austin (w/Enc.)
John Griggs; Commonwealth Edison (w/Enc.)
Susan Smith; Owens-Illinois (w/Enc.)

Proceedings of the Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Remediation Conference

November 29 - December 1, 1995 • Houston, Texas

The 1994 Petroleum Hydrocarbons Conference/Expo was sponsored by the National Ground Water Association and the American Petroleum Institute, and was comprised of 3 days of technical presentations which covered the following topic areas:

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A New Application of a Proven Remediation Tool: Bioventing
Natural Bioremediation: A Reasonable Alternative
Soil Vapor Extraction
Use of Ground Water Modeling for Remediation
Use of Biofilters for Offgas Treatment
Free Phase and Dissolved Phase Hydrocarbon Recovery

In addition, more than 100 leading companies in the ground water and petroleum idustries participated in the Conference Exposition in which a variety of equipment and services for preventing, detecting, and remediating ground water contaminated by petroleum hydrocarbons and other organic chemicals were showcased.

This bound volume is a compilation of papers that were presented at the Conference. Materials appearing in the publication are indexed to Ground Water On-Line, the data base of the National Ground Water Information Center at (614) 761-3222

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Suzy Colley, Graphics

Communications and Business Correspondence: Ground Water Management, 6375 Riverside Drive, P.O. Box 9050, Dublin, Ohio 43017-0950, Tel: (800) 551-7379, (614) 761-1711, Fax: (614) 761-3446

RESULTS OF A MULTI-SITE FIELD TREATABILITY TEST FOR BIOSLURPING: A COMPARISON OF LNAPL RATES USING VACUUM-ENHANCED RECOVERY (BIOSLURPING), PASSIVE SKIMMING, AND PUMP DRAWDOWN RECOVERY TECHNIQUES

J.A. Kittel and Andrea Leeson
Battelle Memorial Institute, Columbus, Ohio

R.E. Hinchee
Parsons Engineering Science, South Jordan, UT

R.E. Miller and P.E. Haas
Air Force Center for Environmental Excellence, Brooks AFB, Texas

Bioslurping is a new dynamic technology designed to efficiently recover free-floating petroleum hydrocarbons (free product) from the subsurface while simultaneously enhancing natural biodegradation of petroleum hydrocarbons in the vadose zone. Bioslurping is a vacuum-enhanced fluids pumping technology that simultaneously extracts groundwater, free product, and soil gas in the same process stream. The U.S. Air Force has initiated a multi-site program to evaluate the widespread application of bioslurping at free product-contaminated Air Force sites. The Air Force Bioslurper Initiative is designed to access the field application of the bioslurping technology at 36 Air Force sites. The field studies are designed to evaluate the efficacy of bioslurping for the recovery of free-floating fuel (free product) and to evaluate the potential for bioventing to enhance natural biodegradation of petroleum contaminants.

The technical approach for conducting the bioslurper pilot tests includes assessing the geologic and hydrologic characteristics of each site, free-product baildown testing in site monitoring wells, soil gas analysis, and a bioslurper pump test. Bioslurping free-product recovery efficiency is compared to conventional skimming and dual-pump free-product recovery technologies, and bioventing potential is assessed via in situ respiration testing. The Air Force field program was initiated in July 1994. At the time of this writing, seven field tests have been completed. At each site bioslurping has yielded the highest LNAPL recovery rate. This paper presents a summary of LNAPL recovery data to date. Operational issues such as permitting and treatment of vapor and wastewater discharge will be discussed.

Introduction

This paper presents results to date of field testing conducted under the Bioslurper Initiative which is funded and managed by the U.S. Air Force Center for Environmental Excellence (AFCEE) Technology Transfer Division. The AFCEE Bioslurper Initiative is a multi-site program designed to evaluate the efficacy of bioslurping technology for (1) recovery of light, nonaqueous-phase liquid (LNAPL) from groundwater and the capillary fringe, and (2) enhancement of natural in situ biodegradation of petroleum contaminants in the vadose zone via bioventing.

Objectives

The main objective of the Bioslurper Initiative is to develop procedures for evaluating the potential for recovering free-phase LNAPL present at petroleum-contaminated sites. The overall study is designed to evaluate bioslurping and to identify site parameters that are reliable predictors of bioslurping performance. To measure LNAPL recovery in a wide variety of in situ conditions, tests are being performed at many sites.

The purpose of the field testing is to collect data to support determination of the predictability of LNAPL recovery and to evaluate the applicability, cost, and performance of the bioslurping technology for removal of free product and remediation of the contaminated area. Although bioslurping had been demonstrated to enhance LNAPL recovery at a large field site (Kittel et al., 1994), its efficacy relative to other LNAPL recovery technologies had not been fully investigated. The Bioslurper Initiative on-site testing was structured to allow direct comparison of LNAPL recovery achieved by bioslurping with the performance of more conventional LNAPL recovery technologies. The test method included an initial evaluation of site variables followed by LNAPL recovery testing. The three technologies used to recover free LNAPL floating on the water table are skimmer pumping, bioslurping, and drawdown pumping. This paper presents results of the comparative LNAPL recovery rates by each technique used at the sites completed to date. An overview of the techniques utilized to perform the Bioslurper Initiative field testing is presented below. An in-depth presentation of the Bioslurper Initiative field procedures has been published elsewhere (Leeson et al., 1995).

Bioslurper Technology

Bioslurping is a new dynamic technology that utilizes construction vacuum dewatering technology to facilitate vacuum-assisted free-product recovery and bioventing to simultaneously recover free product and remediate the vadose zone. Unlike other LNAPL recovery technologies, bioslurping systems treat two separate geologic media simultaneously. Bioslurping pumps are designed to extract free-phase LNAPL from the water table and to aerate vadose zone soils through soil gas vapor extraction. The bioslurper system also can be designed to achieve hydraulic control as is done with conventional pump-and-treat technology. The system withdraws groundwater, free product, and soil gas in the same process stream using a single pump. Groundwater is separated from the free product and is treated (when required) and discharged. Free product is recovered and can be recycled. Soil gas vapor is treated (when required) and discharged.

Bioslurping may improve free-product recovery efficiency without requiring the extraction of large quantities of groundwater. The bioslurper system pulls a vacuum of up to 20 inches of mercury on the recovery well to create a pressure gradient to force movement of LNAPL into the well. The system is operated to cause very little drawdown in the aquifer, thus reducing the problem of free-product entrapment in the aquifer.

Bioventing of the vadose zone soils is achieved by withdrawing soil gas from the recovery well. The slurping action of the bioslurper system cycles between recovering liquid (free product and/or groundwater) and soil gas. The rate of soil gas extraction is dependent on the recovery rate of liquid into the well. When free-product removal activities are complete, the bioslurper system is easily converted to a conventional bioventing system to complete remediation of the vadose zone soils.

Bioslurper systems are designed to minimize environmental discharges of groundwater and soil gas. As done in bioventing, bioslurper systems extract soil gas at a low rate to reduce volatilization of contaminants. In some instances volatile discharges can be kept below treatment action levels. The slurping action of a bioslurping system greatly reduces the volume of groundwater that must be extracted compared to conventional LNAPL recovery systems, thus greatly reducing groundwater treatment costs.

A significant feature of the bioslurping process is the induced airflow, which in turn induces LNAPL flow toward the well. The pressure gradient created in the air phase results in a driving force on the LNAPL that is significantly greater than that which can be induced by pumping the LNAPL with no airflow. Also of importance is the fact that the airflow created by the vacuum actually enhances the LNAPL content around the well. That is, the LNAPL tends to accumulate or pile up around the well. The accumulation around the well ensures that the permeability controlling the conductivity to LNAPL is maximum. For these reasons, bioslurping has the potential for removing more LNAPL and at greater rates than do other pumping mechanisms.

Pilot Test Procedures

The U.S. Air Force has selected sites to participate in the Bioslurper Initiative that represent a broad cross section of LNAPL types, geologic/hydrogeolgic environments, and regulatory settings. To ensure consistency in testing procedures, the *Test Plan and Technical Protocol for Bioslurping* (Battelle, 1995) was developed as overall guidance to support preparation of site-specific Test Plans for each of the more than 35 sites where short-term field tests will be conducted (Figure 1). The overall protocol contains details on the general materials and methods for bioslurper testing. The bioslurper protocol was developed from a similar protocol for bioventing (Hinchee et al., 1992).

Table 1 presents the schedule of activities for each short-term pilot test. Initial site characterization activities are conducted to evaluate site variables that may affect LNAPL recovery efficiency, and to determine the bioventing potential of the sites. These activities include estimating the persistence of LNAPL in site monitoring wells through baildown tests, soil sampling to determine physical/chemical site characteristics, determining soil gas permeability to estimate the well's radius of influence, and in situ respiration testing to evaluate microbial activity. The site characterization approach is aimed at providing data to assist in determining the feasibility of product recovery as well as aid in the design of the pilot- or full-scale system.

Following the site characterization activities, a short-term bioslurper pilot test is conducted. A bioslurper system is installed on a single selected well and typically is operated as follows: 2 days in the skimmer mode (no vacuum); 4 days in the bioslurper mode (vacuum-mediated); 1 day in the skimmer mode (follow-up repeatability test); and 2 days in the groundwater depression mode. Measurements of the extracted soil gas composition, free-product thickness,

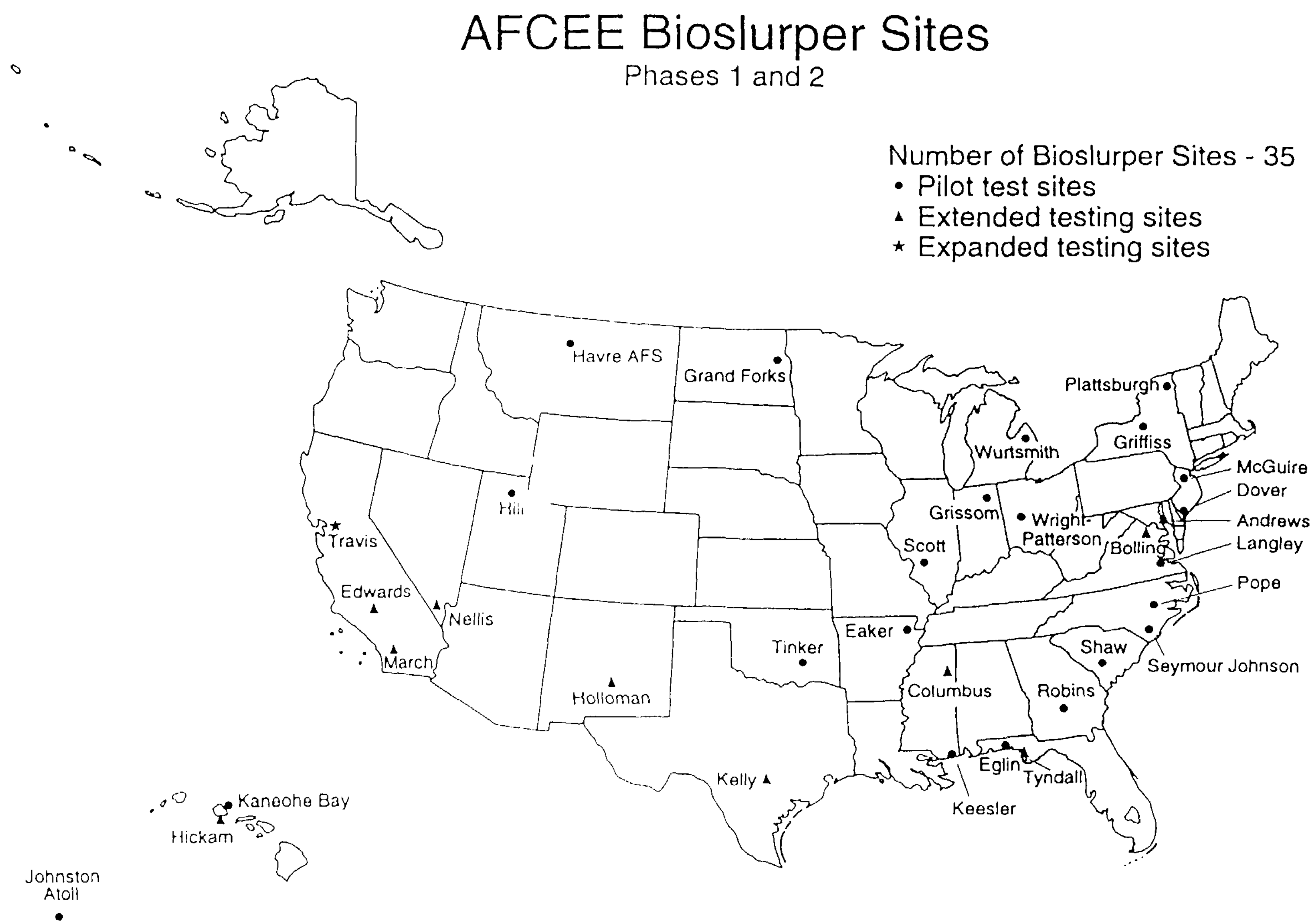

Figure 1. AFCEE Bioslurper Initiative Sites (Phases 1 and 2).

and groundwater level are made during the pilot test. The volume of extracted free product is quantified over time. These measurements are used to evaluate the long-term effectiveness of bioslurping.

The U.S. Air Force has already installed monitoring points or other wells at many sites that are suitable for use in this study. In keeping with the objective of developing a cost-effective program for site remediation, every effort is made to use existing wells and to minimize drilling costs.

Table 1. Schedule of Activities for Bioslurper Initiative

Pilot Test Activity	Schedule
Mobilization	day 1-2
Site Characterization	day 2-3
Baildown Tests	
Slug Test	
Soil Gas Survey (limited)	
Monitoring Point Installation (3 MPs, multiple depths)	
Soil Sampling (TPH, BTEX, and Physical Characteristics only)	
System Installation	day 2-3
Test Startup	day 4
Skimmer Test (2 days)	day 4-5
Bioslurper Pump Test (4 days)	day 6-10
Soil Gas Permeability Testing	day 6
Skimmer Test (continued)	day 11
Drawdown Pump Test (2 days)	day 12
In Situ Respiration Test (air injection only)	day 12
Demobilization/Mobilization	day 13-14

The Bioslurper Initiative short-term pilot test consists of three different LNAPL recovery tests from a single extraction well. At each site the well that appears to have the highest potential for LNAPL recovery is selected for testing. The bioslurper trailer-mounted pilot system is connected to the well via a 1-inch-diameter pvc droptube. Each trailer-mounted unit includes a bioslurper liquid ring pump (3-hp to 7.5-hp), a gasoline- or diesel-powered electrical generator capable of supplying all power requirements for the pilot testing, an oil/water separator with 10-gpm flow capacity, a transfer tank and pump for directing extracted groundwater to the base-supplied effluent disposition system, and vapor treatment equipment (Figure 2).

The drop tube is positioned at the oil/water interface in the well. The selection of the depth of the drop tube is based on observations made of changes in water levels during the baildown test to compensate for depression of the water level in the well caused by excessive LNAPL thicknesses. The position of the drop tube is the same for skimmer and bioslurper test configurations. During the skimmer test the well is open to the atmosphere (no vacuum), during the bioslurper test the wellhead is sealed vacuum tight with a sanitary well seal. For the pump drawdown test the drop tube is set 1 to 3 ft below the oil/water interface in the well, with the well open to the atmosphere.

Results

Short-term pilot tests have been completed at 11 sites at the time of this writing. Table 2 identifies the sites where testing has been completed and summarizes site characteristic data for each site. A summary of LNAPL recovery data for each pilot test is presented in Table 3. The amount of LNAPL recovered is shown in terms of gallons per day for each of the technologies tested. At 9 of the 11 sites, the bioslurping configuration recovered more LNAPL than either the skimmer or drawdown configurations; in some cases, nearly an order of magnitude increase was observed in LNAPL recovery rates. At Hickam AFB, the drawdown configuration recovered LNAPL at a higher rate than did bioslurping. However, upon further inspection of the extraction well after testing was completed, it was discovered that the well's screen extended to near the ground surface, causing short-circuiting of the vacuum to the atmosphere. At Travis AFB bioslurping and drawdown testing recovered LNAPL at approximately the same rates. At the Travis site it was necessary to dewater during each phase of the testing to facilitate any LNAPL recovery due to an unusually high water table caused by heavy rains.

It should be noted that the average LNAPL recovery rates presented in Table 3, while accurately portraying the relative LNAPL recovery rates of each test configuration, do not necessarily represent long-term sustainable LNAPL recovery rates. Figures 3 through 7 present graphs of representative LNAPL recovery curves observed during the testing. Generally, in each test configuration the LNAPL recovery rate is much higher at the start of the test than at the end of the test. After 4 days of extraction in the bioslurper mode, the LNAPL recovery rates are still higher than for skimming or drawdown testing which are operated for shorter time periods.

Vapor and Wastewater Treatment Issues

The relative costs of bioslurper implementation are being evaluated as part of the Bioslurper Initiative. Of particular importance are the costs of vapor and groundwater discharge treatment. The vapor discharge characteristics vary widely from site to site largely due to site-specific LNAPL composition and system flow rate (Table 4). In addition to having variable discharge characteristics, vapor treatment requirements vary greatly depending on the state and locality of the test site. In general, sites where the LNAPL is less volatile than JP-4 jet fuel (JP-5, diesel,

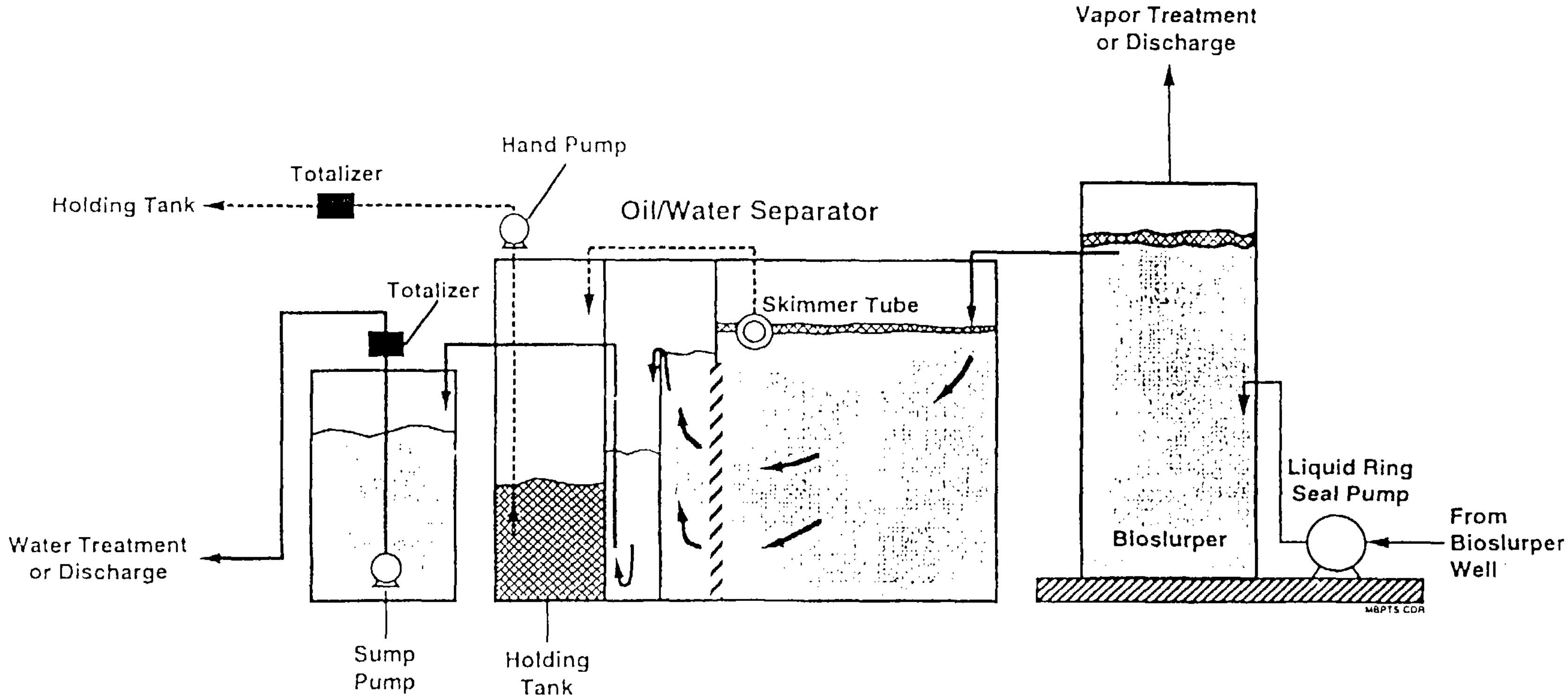

Figure 2. Diagram of Trailer-Mounted Bioslurper Pilot Test System

Table 2. Bioslurper Initiative Site Characteristic Summary Data

Base Location	Site ID	LNAPL Type	Depth to Water (ft)	Initial Fuel Thickness (ft)	Fuel Thickness After 24 hr Baildown Test (ft)	Extraction Well Diameter (in)
Bolling AFB, D.C.	Bldg. 18	fuel oil	23.65	4.44	3.52	2
Bolling AFB, D.C.	Bldg. 41	gasoline	19.06	0.34	0.34	4
Andrews AFB, MA	Bldg. 1845	fuel oil	15.36	2.32	2.01	4
Wright-Patterson AFB, OH	Well P6-2	JP-4	20.69	0.12	0.05	2
Travis AFB, CA	JFSA-1	JP-4	8.7	NA[1]	NA	6
Robins AFB, GA	UST 70/72	JP-4	8.5	6.67	1.83	4
Robins AFB, GA	SS010	JP-4	7.3	6.78	0.16	2
Kaneohe MCBH, HI	POL Tank Farm	JP-5	17.54	1.13	0.24	2
Hickam AFB, HI	Area H	AVGAS	18.59	3.98	3.95	4
Johnston Atoll DNA	Tank 41	JP-5	7.78	0.44	0.57	2

[1] A skimmer LNAPL recovery system was operating at this site prior to beginning field testing.

Table 3. Bioslurper Initiative Comparative Fuel Recovery Rates and Bioventing Feasability Study

Base Location	Site ID	Average Fuel Recovery (gal/day)				Soil Gas Radius of Influence (ft)	Biodegradation Rate (mg/kg/day)
		2-Day Skimmer Test	4-day Bioslurper Test	1-Day Skimmer Test	2-Day Drawdown Test		
Bolling AFB, D.C.	Bldg. 18	16.9	59.8	8.2	31.2	45	NA
Bolling AFB, D.C.	Bldg. 41	0.86	1.14	NA	0.13	47	12.9 to 15.3
Andrews AFB, MA	Bldg. 1845	8.7	78.5	0.7	NA	250	21 to 7.5
Wright-Patterson AFB, OH	Well P6-2	4.0	4.65	NA	2.46	10.0	1.3 to 3.2
Travis AFB, CA	JFSA-1	0.0	3.85	0.0	3.76	55.3	61 to 82
Robins AFB, GA	UST 70/72	10.85	47.5	4.96	11.5	56	1.8-3.3
Robins AFB, GA	SS010	1.41	3.22	NA	0.36	76	6.9-10.7
Kaneohe MCBH, HI	POL Tank Farm	0.0	2.39	0.05	0.0	23	60 to 122
Hickam AFB, HI	Area H	34.5	90.9[1]	NA	408.5	NA[1]	5.1 to 21
Johnston Atoll DNA	Tank 41	29.8	56	3.6	9.5	15.0	3.9 to 8.0

NA Test not performed.
[1] Extraction well screen extended to the ground surface causing short-circuting.

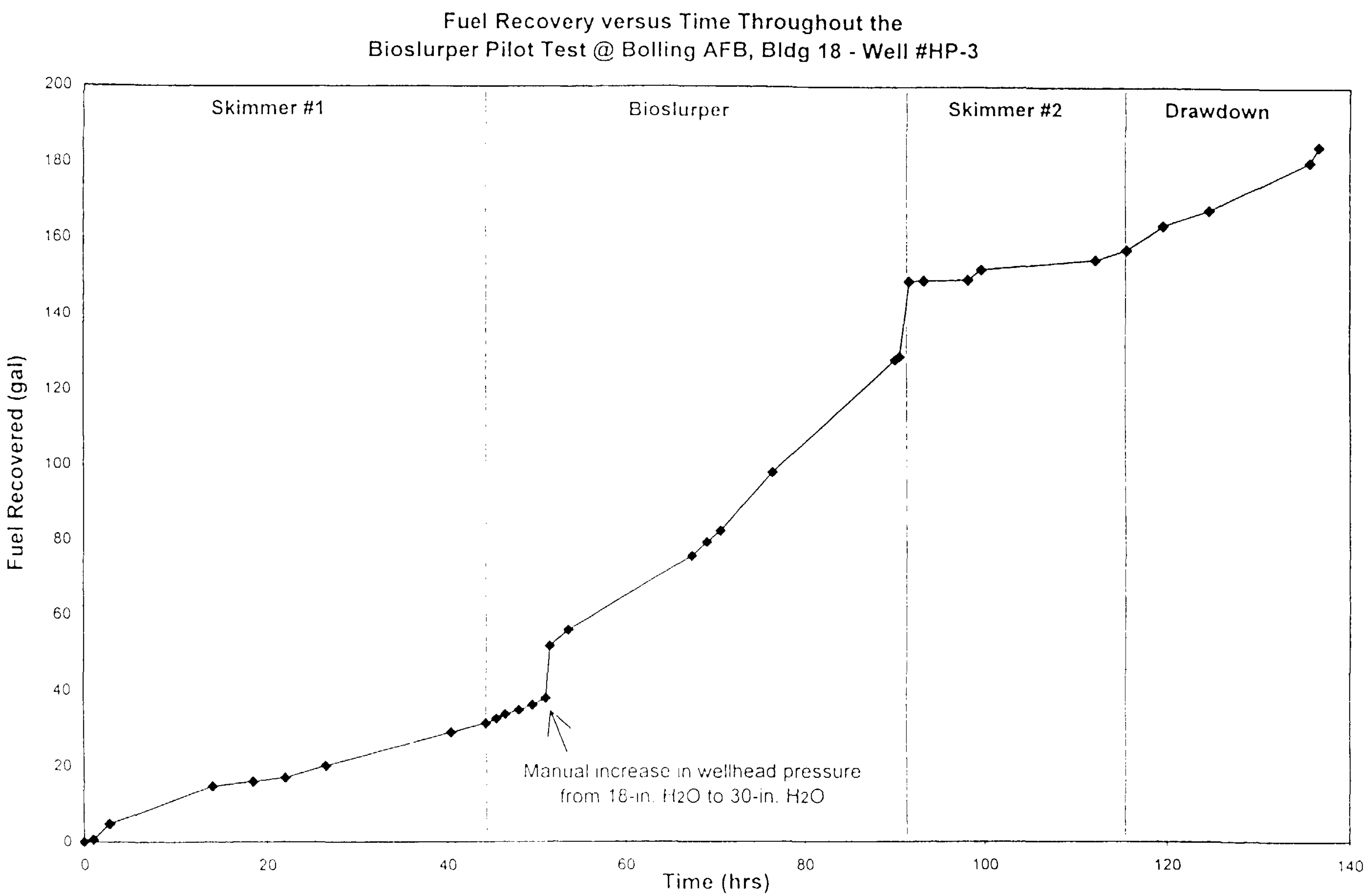

Figure 3. Fuel Recovery versus Time Throughout the Bioslurper Pilot Test @ Bolling AFB, Bldg. 18 - Well #HP-3

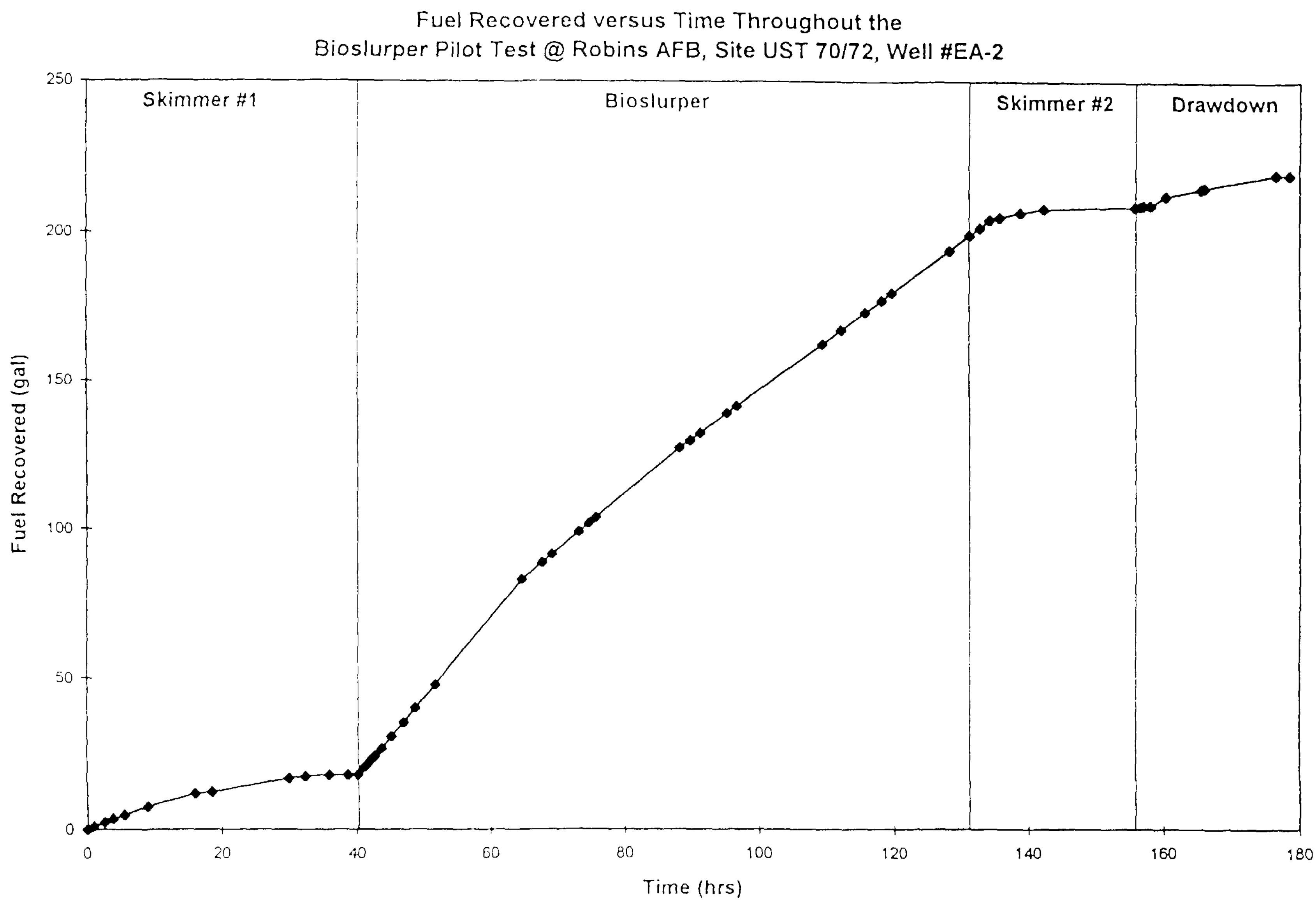

Figure 4. Fuel Recovery versus Time Throughout the Bioslurper Pilot Test @ Robins AFB, Site UST 70/72, Well #EA-2

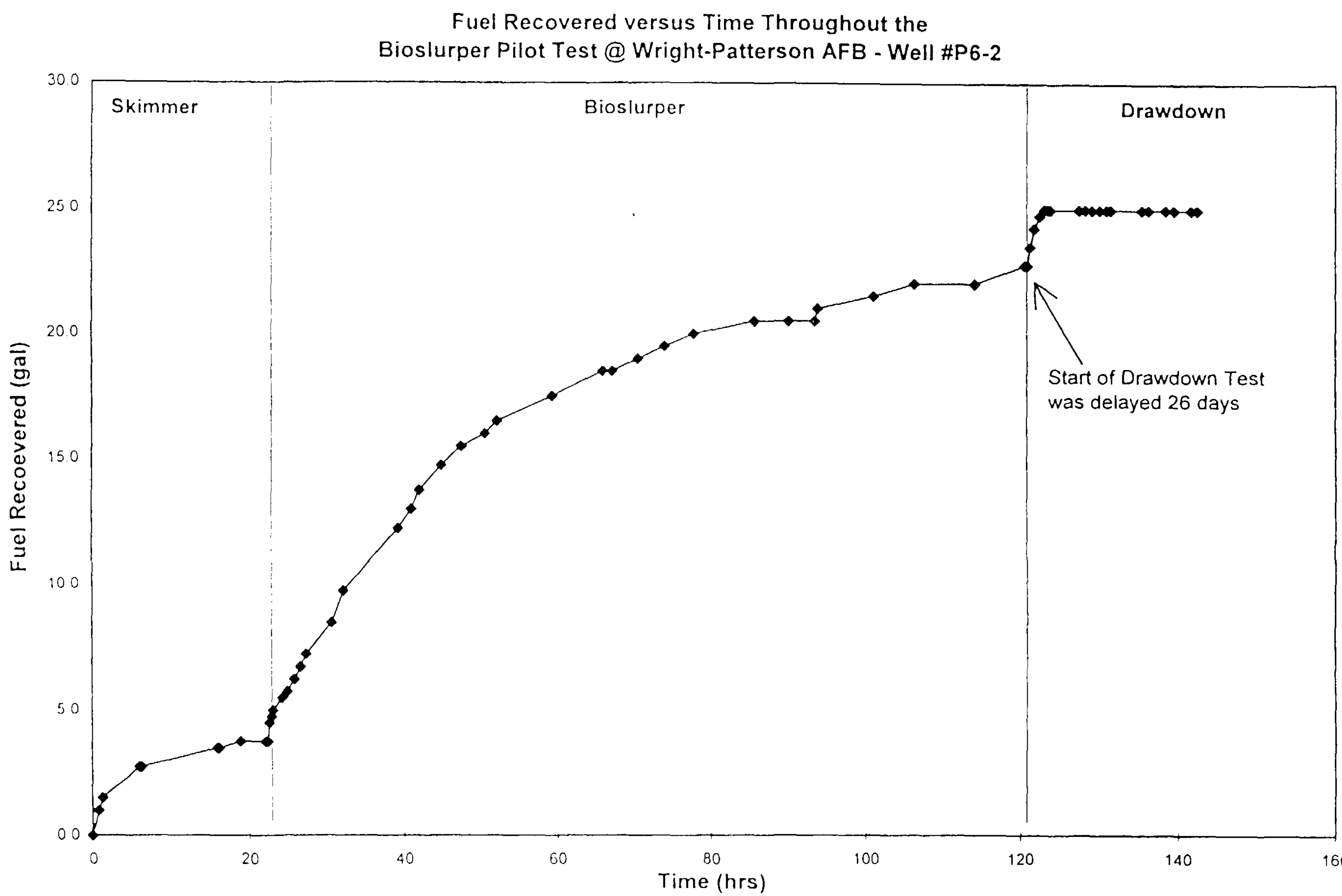

Figure 5. Fuel Recovery versus Time Throughout the Bioslurper Pilot Test @ Wright-Patterson AFB, Well #P6-2

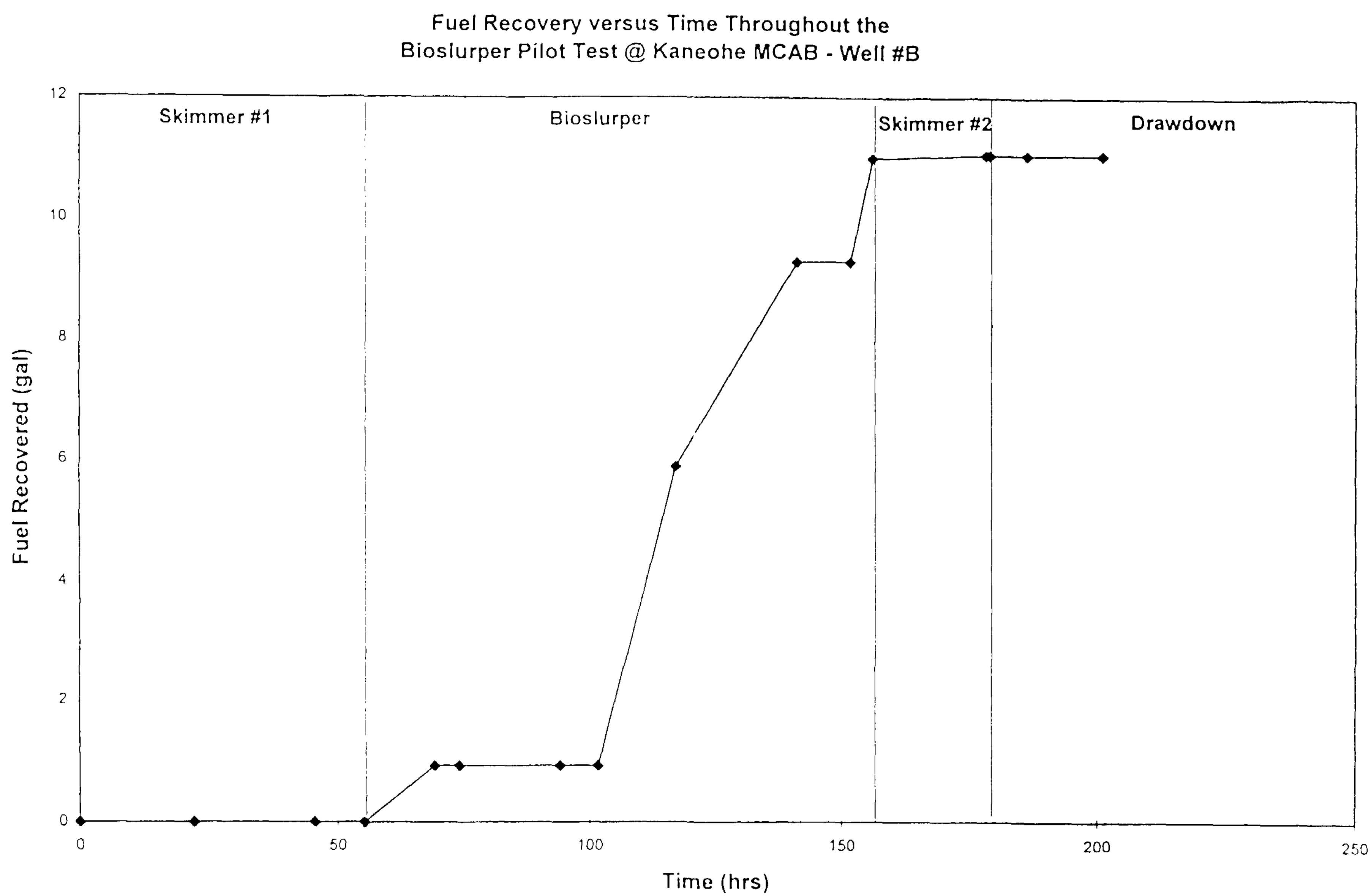

Figure 6. Fuel Recovery versus Time Throughout the Bioslurper Pilot Test @ Kaneohe MCAB - Well #B

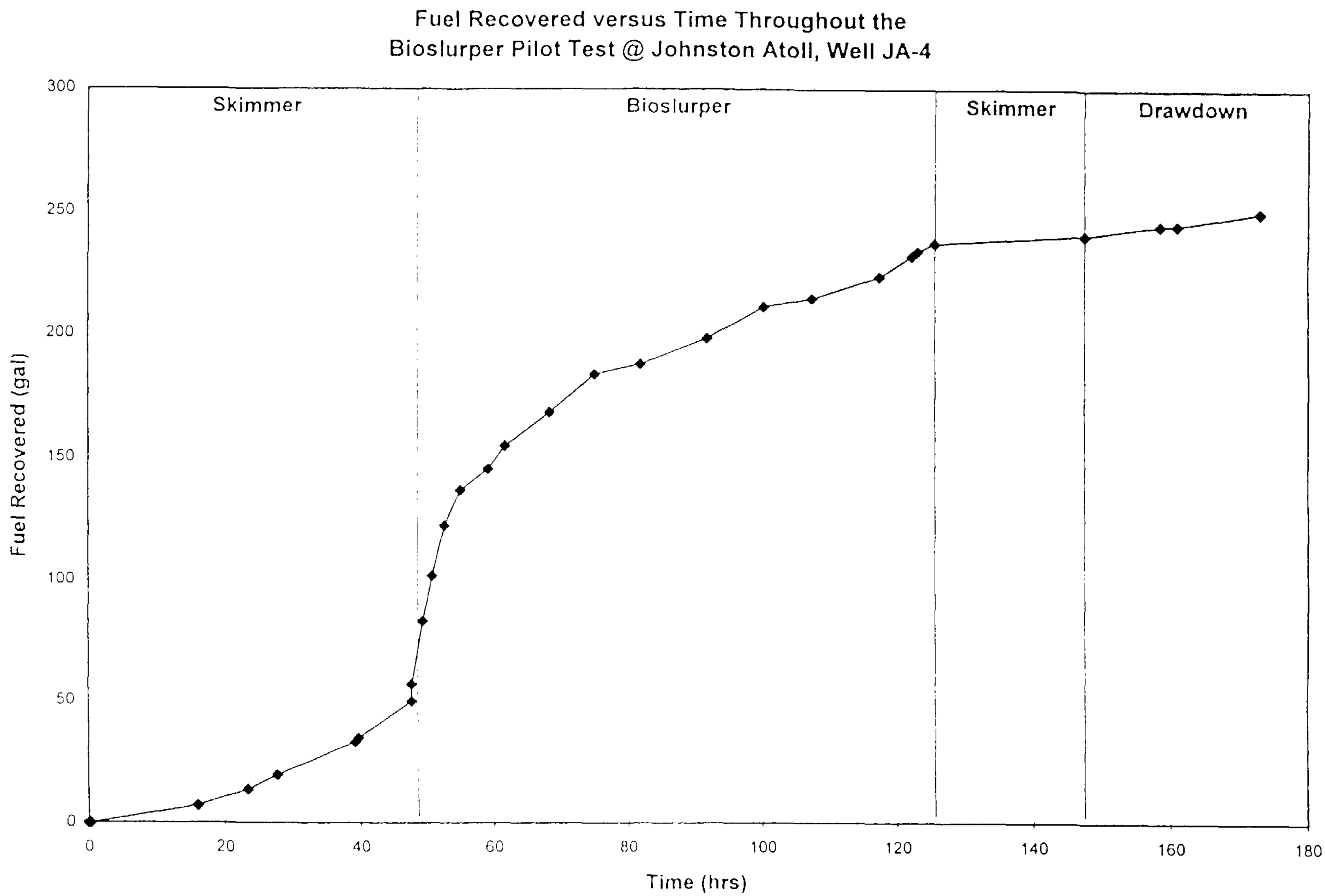

Figure 7. Fuel Recovery versus Time Throughout the Bioslurper Pilot Test @ Johnston Atoll, Well JA-4

fuel oil, etc.) have not required vapor treatment prior to discharge. At sites where the LNAPL is equal to or more volatile than JP-4 (AVGAS, gasoline, etc.), vapor treatment often has been required. Vapor treatment options are similar to those available for soil venting projects. Due to the relatively short-term nature of LNAPL recovery projects, the use of internal combustion engines appears to be an attractive treatment option.

Table 4. Benzene and TPH Vapor Discharge Levels at Bioslurper Test Sites

Site Location	Fuel Type	Extraction Rate (scfm)	Benzene (ppmv)	TPH (ppmv)	Benzene Discharge (lb/day)	TPH Discharge (lb/day)
Andrews AFB	No. 2 Fuel Oil	8.0	16	2,000	0.0010	0.20
Site 1, Bolling AFB	No. 2 Fuel Oil	4.0	0.20	153	0.00030	0.0090
Site 2, Bolling AFB	Gasoline	21	370	70,000	2.3	470
Johnston Atoll	Jet Fuel	10	0.60	975	0.0017	5.7
Travis AFB	Jet Fuel	20	100	10,800	0.58	130
Wright-Patterson AFB	Jet Fuel	3.0	ND	595	0	1.0

ND = not detected.

Treatment of discharged groundwater generally is also required. At many sites it is possible to discharge separated groundwater directly to the sanitary sewer. At sites where the LNAPL is a low-volatility fuel, treatment for oil/water emulsions usually is necessary. Several options are available, all of which involve some level of physical separation. Using large pore bag filters (100 to 200 micron) and additional holding tanks to increase the residence time for the aqueous wastestream have been most successful. The use of surface-modified clay has also given positive results to reduce total petroleum hydrocarbon concentrations from the 100 to 150 ppm range to less than 25 ppm for discharge to the sanitary sewer. However, this option is not useful for treatment of benzene, toluene, ethylbenzene, and xylenes (BTEX).

SUMMARY

Data collected to date on the AFCEE Bioslurper Initiative indicate a dramatic increase in LNAPL recovery rates due to vacuum-enhanced extraction using dewatering technology

(bioslurping). Bioslurping has also been demonstrated to enhance natural biodegradation through forced aeration (bioventing) as indicated in Table 2.

The Air Force Bioslurper Initiative is designed to assess the field application of the bioslurping technology at multiple Air Force sites. Data from the Bioslurper Initiative will be used to evaluate the feasibility of bioslurping in comparison to conventional technologies. In addition, site characterization data will be evaluated to determine which site parameters aid in determining the potential feasibility of bioslurping at a specific site.

The technical approach for conducting the bioslurper pilot tests includes assessing the geologic and hydrologic characteristics of each site, free-product baildown testing in site monitoring wells, soil gas analysis, and a bioslurper pump test. Bioslurping free-product recovery efficiency is compared to conventional skimming and dual-pump free-product recovery technologies. Bioventing potential is assessed via in situ respiration testing. Preliminary results to date demonstrate that bioslurping shows higher free-product recovery rates than conventional technologies. In some instances, recovery rates during bioslurping are an order of magnitude higher than with conventional technologies. These results indicate the potential feasibility of bioslurping as an alternative LNAPL recovery technology.

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Jeffrey A. Kittel is a Program Manager in the Environmental Restoration Department at Battelle Memorial Institute in Columbus, Ohio. Mr. Kittel is responsible for design, installation and management of bioremediation field technology demonstrations. Mailing Address: Battelle, 505 King Ave., Columbus, Ohio 43201. Phone: (614) 424-6122, FAX (614) 424-3667.

Andrea Leeson is a Principal Research Scientist in the Restoration Technology Department at Battelle Memorial Institute in Columbus, Ohio. Dr. Leeson is responsible for design, installation and management of bioremediation field technology demonstrations. Mailing Address: Battelle, 505 King Ave., Columbus, Ohio 43201. Phone: (614) 424-5942. FAX (614) 424-3667.

Dr. Robert E. Hinchee was a Senior Research Leader in the Environmental Restoration Department at Battelle and was the lead technical manager for Battelle's in situ bioremediation research projects. Mailing Address: Parsons Engineering Science, 406 West South Jordan Parkway, Suite 300, South Jordan, Utah 84095,. Phone: (801) 572-5999, FAX (801) 572-9069.

Lt. Col. Ross Miller leads at the Air Force Center for Environmental Excellence (AFCEE) Technology Transfer Division, Brooks AFB, Texas. AFCEE evaluates emerging environmental technologies for effectiveness and provides support at the Air Force Base level to implement site remediation technologies. Mailing Address: Headquarters Air Force Center for Environmental Excellence, 8001 Arnold Drive (Building 642), Brooks AFB, TX 78235.

Patrick Haas is a Project Manager at the Air Force Center for Environmental Excellence (AFCEE) Technology Transfer Division, Brooks AFB, Texas. Mr. Haas is the project manager for the AFCEE Bioslurper Initiative. Mailing Address: Headquarters Air Force Center for Environmental Excellence, 8001 Arnold Drive (Building 642), Brooks AFB, TX 78235. Phone: (210) 536-4314, FAX (210) 536-4309.

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Suzy Colley, Graphics

Communications and Business Correspondence: Ground Water Management, 6375 Riverside Drive, P.O. Box 9050, Dublin, Ohio 43017-0950, Tel: (800) 551-7379, (614) 761-1711, Fax: (614) 761-3446

BIOSLURPING — VACUUM-ENHANCED FREE-PRODUCT RECOVERY COUPLED WITH BIOVENTING: A CASE STUDY

Jeffrey A. Kittel
Battelle, Columbus, OH

Robert E. Hinchee
Battelle, Columbus, OH

Ron Hoeppel
Naval Facilities Engineering Service Center
Port Hueneme, CA

Ross Miller
Air Force Center for Environmental Excellence
Brooks AFB, TX

ABSTRACT

Bioslurping is a new, innovative approach to site remediation at petroleum-release sites that have free-phase light, nonaqueous-phase liquid (LNAPL) contamination. Bioslurper systems are designed to recover free-phase LNAPL, via vacuum-enhanced pumping, while simultaneously initiating the remediation of the vadose zone soils via bioventing. In most applications, a single aboveground vacuum pump can be plumbed to multiple extraction wells to extract LNAPL, groundwater, and soil gas in the same process stream. LNAPL recovery is enhanced by the vacuum-induced gradient, which increases the rate of fluid flow into extraction wells. The system is configured to maximize the removal of LNAPL while minimizing the volume of groundwater that must be extracted. Soil gas is extracted at a low rate to aerate (biovent) the soils and to minimize volatilization.

A bioslurper system installed at Fallon Naval Air Station, Nevada, uses a 10-hp liquid ring pump to extract LNAPL (JP-5), groundwater, and soil gas from 48 extraction wells. As of March 1994, 14 months after startup, more than 8,100 gallons of LNAPL had been recovered. LNAPL recovery rates have ranged from 15 to 60 gpd, the groundwater extraction rate has averaged less than 1 gpm, and the soil gas extraction rate has averaged 50 cfm.

This paper gives an overview of the bioslurper technology. Design, operational, and permitting information is presented for the Fallon bioslurper project. And the bioslurper approach to site remediation is contrasted with conventional free-product recovery technologies.

INTRODUCTION TO BIOSLURPING

Bioslurping adapts and applies vacuum-enhanced dewatering technology to the remediation of petroleum-contaminated sites. Bioslurping combines two remedial approaches: (1) bioventing to stimulate bioremediation of petroleum-contaminated soils in situ; and (2) vacuum-enhanced free-product recovery to extract LNAPLs from the capillary fringe and the water table.

Vacuum-Enhanced Pumping Free-Product Recovery

Vacuum-enhanced recovery is a common pumping technique used in construction dewatering projects (Powers, 1981). Vacuum-enhanced pumping involves applying a negative pressure to a well-point system to increase the rate of flow of groundwater into the wells. Vacuum-enhanced pumping recently has been applied to groundwater remediation pump-and-treat systems and to LNAPL recovery systems. Blake and Gates (1986) report increased groundwater extraction rates and increased residual hydrocarbon (LNAPL) recovery with vacuum-enhanced pumping. Blake et al. (1990) applied vacuum-enhanced pumping techniques to hydrocarbon-contaminated sites to facilitate (1) increased liquid recovery and gradient control, (2) vapor and residual hydrocarbon recovery, and (3) combined vapor recovery and gradient control. Reisinger et al. (1993) enhanced groundwater extraction by 47% using vacuum extraction.

Two important factors influence the movement of fluids into a recovery well: hydraulic gradient (head difference) into the well and aquifer transmissivity (the rate of groundwater movement through a unit thickness of the aquifer). Vacuum-enhanced recovery improves recovery rates by increasing hydraulic gradient and increasing aquifer transmissivity. Conventional dual-pump free-product recovery (FPR) systems increase hydraulic gradient into a well by setting a pump below the water table to establish a cone of depression around the well. Free product then flows down the gradient into the well to be recovered by a second extraction pump. Vacuum-enhanced pumping systems use the same concept, except that the cone of depression is actually a cone of reduced pressure around the well. Fluids then flow across the pressure-induced gradient, from higher pressure outside the well to lower pressure inside the well.

The transmissivity of the saturated zone is an intrinsic characteristic of an aquifer and is a function of the hydraulic conductivity and the aquifer saturated thickness. Vacuum-enhanced pumping increases transmissivity by decreasing the pressure head on the aquifer to increase the saturated thickness of the aquifer. The sum effect of the increase in hydraulic gradient and the increase of aquifer transmissivity is to increase the volume of fluids that can be extracted from a well during a unit of time.

Suction lift might appear to limit the application of vacuum-enhanced dewatering. In theory, the maximum suction lift attainable with an extremely efficient vacuum pump is approximately 25 ft, depending on elevation (Powers, 1981). However, lifts greater than the theoretical maximum can be attained when the extracted fluid is not only water but a mixture of soil gas bubbles and groundwater (Powers, 1981). A mixture of soil gas and water, with a specific gravity less than 1.0, can be lifted higher than a standard water column. Extractions that include LNAPL (liquid with a specific gravity < 1.0) add to this effect. Liquid entrainment or entrapment also helps achieve greater suction lift. This phenomenon occurs when the primary extraction fluid is soil gas, rather than a liquid. At high velocities, extracted soil gas can entrap water droplets and carry them to the surface at relatively high total liquid extraction rates.

Bioslurping

When a fuel release occurs, the contaminants may be present in any or all of the three phases in the geologic media: (1) absorbed to the soils in the vadose zone, (2) floating on the water table in free-phase form, and/or (3) in solution phase dissolved in the groundwater. Of the three phases, dissolved petroleum contaminants in the groundwater are of greatest concern due to the risk of human exposure through drinking water. However, because the liquid- and absorbed-phase hydrocarbons act as feedstocks for groundwater contamination, any remedial technology aimed at reducing groundwater contamination must address these contaminant sources.

At many contaminated sites, petroleum is present in both the vadose zone and the capillary fringe as free product. Regulatory guidelines generally require that FPR take precedence over other remediation technologies, and conventional wisdom has been to complete free-product removal activities before initiating vadose zone remediation. This "phased" approach is costly and slow because conventional FPR technologies have little or no effect on soil contamination; when FPR is complete, a second remediation system must be installed and operated to treat residual soil contamination.

Bioslurping is a new, dynamic technology application that teams free-product recovery with bioventing to simultaneously recover free-product and remediate the vadose zone. Bioslurping is a vacuum-enhanced free-phase petroleum recovery technology. Unlike other FPR technologies, bioslurping systems treat two geologic media simultaneously. Bioslurping pumps extract free-phase fuel from the water table and aerate vadose zone soils through soil gas vapor extraction. The systems can be designed to achieve the hydraulic control of conventional "pump-and-treat" technology. The bioslurper system withdraws groundwater, free product, and soil gas in the same process stream with a single pump, separates groundwater from free product, treats it when required, and discharges it. Free product is recovered and can be recycled. Soil gas vapor is treated when required and discharged.

The bioslurper technology is unique because it uses elements of two separate remedial technologies, **bioventing** and **free-product recovery**, to address two separate contaminated media.

1. **Bioventing** – Uses forced aeration to enhance natural in situ bioremediation of petroleum contamination in the vadose zone; accomplished through either air injection or soil gas extraction.

2. **Free-product recovery** – Removes free-phase petroleum from the capillary fringe in liquid form; generally accomplished with a skimmer pump to pump out fuel that enters a monitoring well or a dual-pump recovery system (one pump lowers the water table and increases the flow of fuel into the well due to the gravity-induced gradient, and the second pump skims off the fuel).

Both technologies are widely used. By combining them, bioslurping enhances the capabilities of each used alone. Conventional FPR skimmer systems generally are inefficient because they have little effect on free product outside the recovery well, and they rely on the passive movement of fuel into the recovery well. Dual-pump FPR systems increase recovery efficiency by drawing the water table down several feet to create a hydraulic gradient into the well. Although higher recovery rates are achieved, creation and maintenance of the hydraulic gradient can require extraction of large volumes of groundwater that must be treated prior to discharge. Also, lowering the water table may serve only to trap free product in the newly exposed vadose zone so that it reappears when the water table returns to its normal level.

Bioslurping improves FPR efficiency without extracting large quantities of groundwater. The bioslurper system pulls a vacuum of up to 20 inches of mercury on the recovery well to create a pressure gradient that forces movement of fuel into the well. Bioslurping causes very little drawdown in the aquifer and reduces the problem of free-product entrapment. Bioventing of the vadose zone soils is achieved by withdrawing soil gas from the recovery well. The slurping action of the bioslurper system cycles between recovering liquid (free product and/or groundwater) and soil gas. The rate of soil gas extraction depends on the recovery rate of liquid into the well. When free-product removal activities are complete, the bioslurper system is easily converted to a conventional bioventing system to complete remediation of the vadose zone soils.

Bioslurper systems minimize environmental discharges of groundwater and soil gas. Like bioventing systems, they extract soil gas at a low rate to reduce volatilization of contaminants. Sometimes, volatile discharges can be kept below treatment action levels. The slurping action greatly reduces the volume of groundwater extracted compared to conventional FPR systems, thus reducing groundwater treatment costs. Figure 1 compares conventional dual-pump FPR to bioslurping. The significant features of bioslurping are that it:

1. enhances FPR via vacuum-enhanced pumping;
2. simultaneously treats the vadose zone via bioventing;
3. reduces the ratio of groundwater extracted per gallon of fuel recovered, compared to conventional dual-pump recovery systems;
4. can be designed to dewater to expose contamination below the water table (at sites where water table fluctuations occur) or to achieve hydraulic control;
5. requires only one pump to extract from multiple wells, reducing capital costs;
6. provides suction lift greater than the theoretical maximum due to liquid entrapment;
7. can be converted easily to a conventional bioventing system (air injection or extraction) when FPR activities are completed.

SITE DESCRIPTION

NAS Fallon is located 6 miles southeast of Fallon, Nevada, and 60 miles east of Reno. Established as a military facility in 1942 as part of the Western Defense Program, the base was commissioned as a Naval Air Auxiliary Station (NAAS) in 1944 and was upgraded to Naval Air Station in 1972 (ORNL, 1991). NAS Fallon is an aircraft-weapons delivery and tactical air-combat training facility.

Geologic Setting

The Fallon area is in the northwestern part of the Great Basin. Valley fill consists of great thicknesses of lake-laid materials interwedged with river alluvian and aeolian material deposited during interpluvial periods (USDA, 1975). Soil at the bioslurping site consist primarily of fine sand and clay loam to a depth of ~6 ft (USDA, 1975). Underlying these soils are alternating layers of clay, silty/clayey sand, and sand. At the bioslurping site, surface soils consist of loose sand to approximately 5 ft, followed by alternating layers of varying thicknesses of clay, sandy/silty clay, clayey/silty sand, and sand (Battelle, 1992). Groundwater generally is encountered 5 to 10 ft below the ground surface. Groundwater quality varies greatly across the site, with high dissolved-solids content and high alkalinity in many areas. Groundwater is present at approximately 9 ft below ground surface on the bioslurping site. Free product is visible in most site wells, with apparent free product thicknesses up to 2 ft.

SYSTEM CONSTRUCTION

Well Installation

The 1-acre bioslurper demonstration site is in a vacant field west of the NAS Fallon new fuel farm. During the initial site investigation activities (Battelle, 1992), 48 schedule 40 PVC bioslurper extraction wells were installed south of a JP-5 supply pipeline pumphouse (see Figure 2). The extraction wells were placed on a 30′ × 30′ grid (six rows with 8 wells each) upgradient of a previously defined free-product plume (ORNL, 1991). Bioslurper well construction followed the standard procedures for groundwater monitoring wells; i.e., inside a 4.25 inch hollow stem auger at depths ranging from 12.0 ft to 16.5 ft, with 5.0 ft to 7.0 ft (10 slot) screened intervals (Battelle, 1992). A medium-grade silica sand was installed across the screened interval of each well, with a hydrated bentonite seal near the surface and a concrete cap at the surface. Each well was completed with a 6-inch riser. Four groundwater monitoring wells and one uncontaminated background monitoring well also were installed.

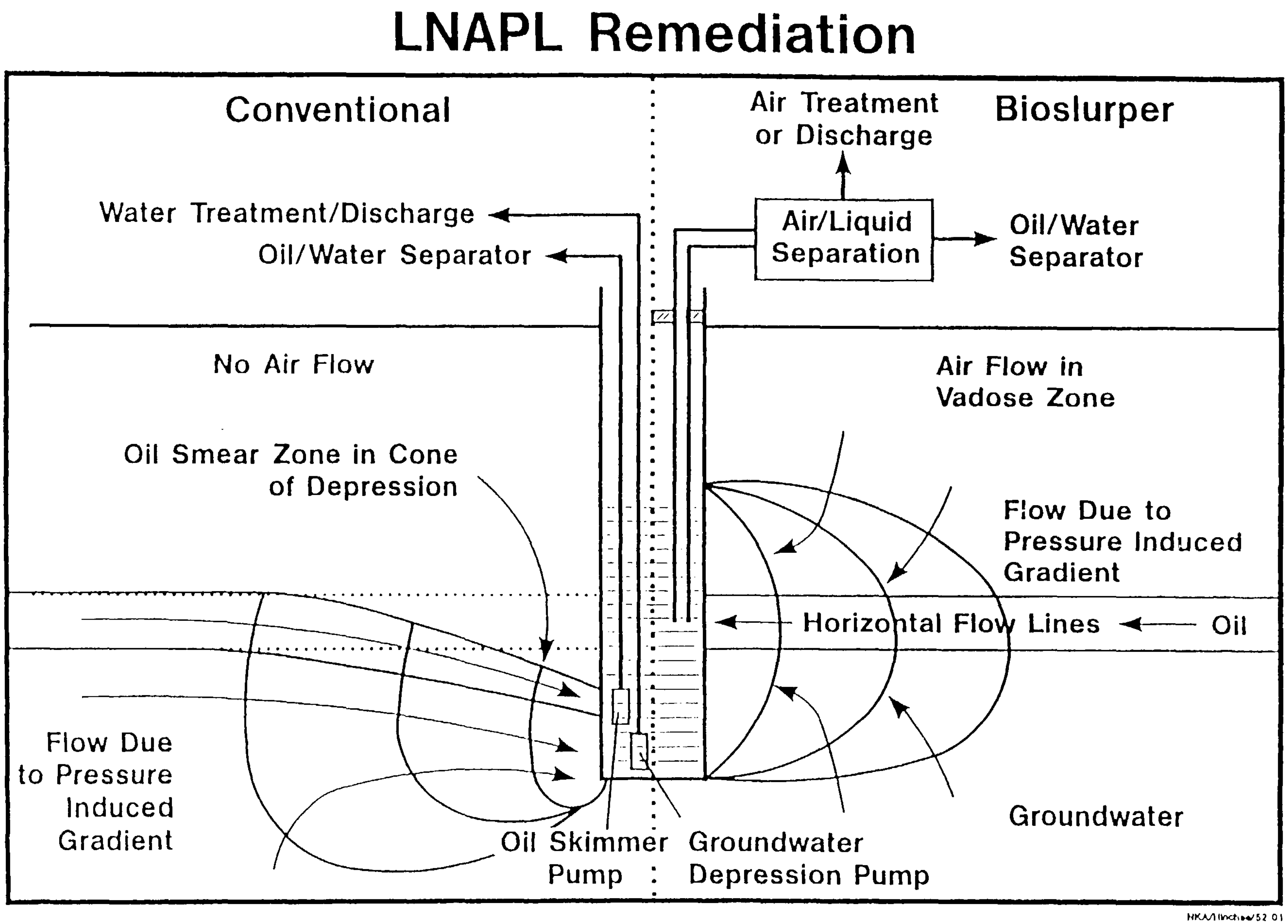

Figure 1. Comparison of Conventional Dual-Pump Free-Product Recovery and Bioslurping

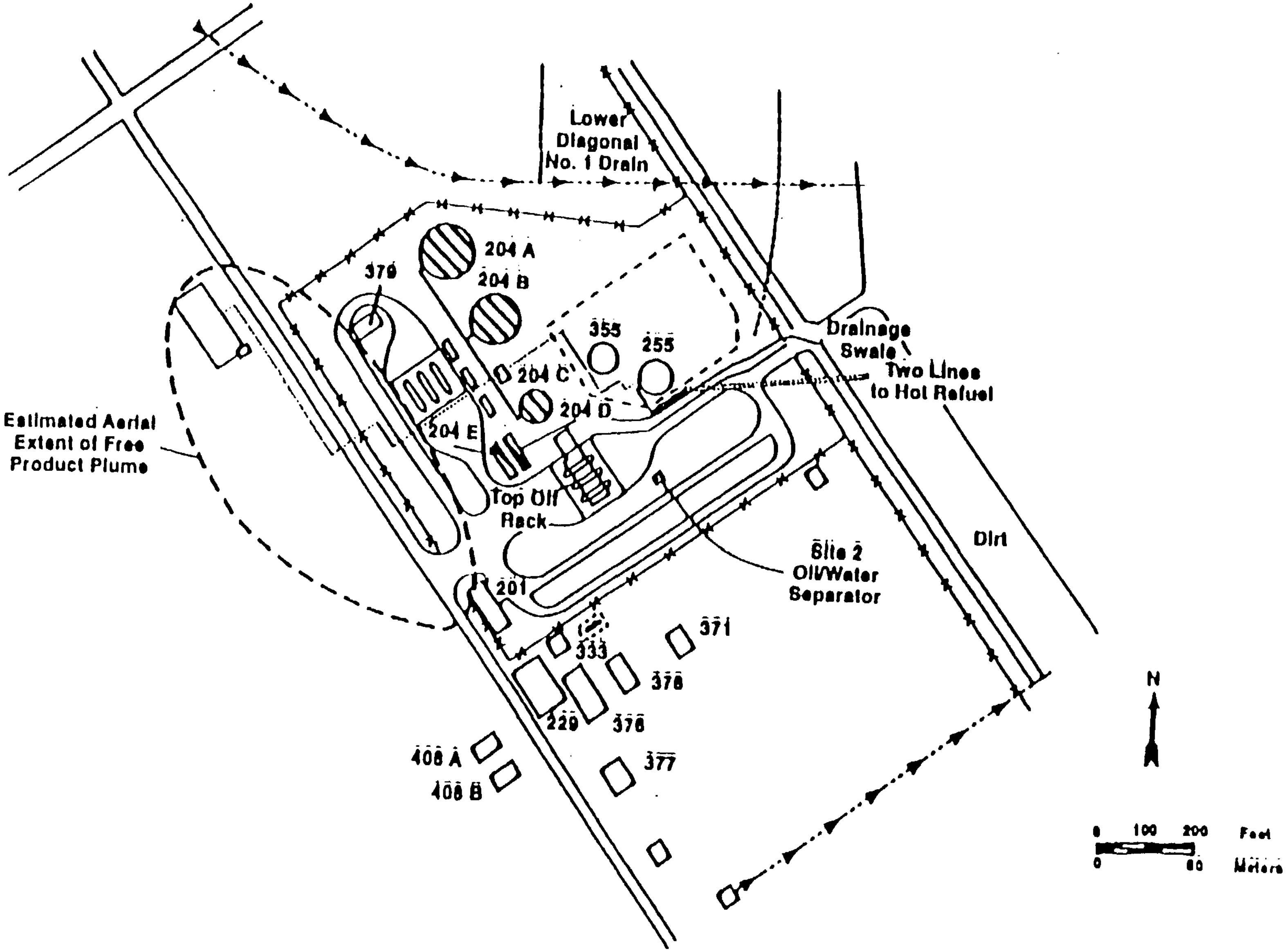

Figure 2. Estimated Aerial Extent JP-5 Free Product Plume West of NAS New Fuel Farm. Bioslurper System Treats an Approximate 1-Acre Plot Within Plume

System Components

Figure 3 shows the aboveground components of the Fallon bioslurper system. The bioslurper pump is a 10-hp (460-V, 3-phase) liquid ring pump capable of air extraction rates up to 130 cfm, and groundwater extraction rates up to 30 gpm. A 24-gpm oil-water separator (Megator Corp., Pittsburgh, PA) is connected to the pump-effluent line to receive groundwater and free product. A 500-gal fuel tank receives any skimmed product, and groundwater gravity-drains into a 140-gal PVC transfer tank. A 5-hp, float-switch-activated irrigation pump transfers groundwater to the NAS Fallon sanitary sewer. A flow totalizer meter quantifies the volume of groundwater discharged to the sanitary sewer.

The bioslurper pump is connected to a 6-inch-diameter schedule 40 PVC manifold that splits into three banks to tie into each bioslurper well via 1-inch-diameter suction lines. Figure 4 shows the bioventing system well layout and manifold configuration. Each 1-inch suction line is connected to a 1-inch PVC drop tube, which enters the wellhead through a vacuum-tight seal and extends to the groundwater/product interface in each well (see Figure 5). A 12-inch section of clear PVC tube at the top of the drop tube allows for visual inspection of extraction fluids. A 2-inch tee and a ball valve were placed at the wellhead of each extraction well to allow for release of the vacuum from the well.

SYSTEM STARTUP

Process Monitoring

In conjunction with the full-scale startup, a process monitoring program was put in place to evaluate the performance of the bioslurper system. The monitoring program tracks the mass of petroleum hydrocarbons removed in liquid, dissolved, and gaseous forms. In situ respiration tests are conducted to determine biodegradation rates and the mass of JP-5 mineralized. Free-product recovery volumes are measured daily by pumping the fuel out of the 500-gal steel holding tank into a 4,000-gal holding tank supplied by NAS Fallon. Fuel volume is quantified via a flow totalizer on the transfer pump. Recovered fuel is removed from the site and recycled. Monthly water samples are taken from the oil/water separator (OWS) effluent to track dissolved petroleum concentrations and to confirm proper operation of the OWS. Vapor discharge is sampled periodically at the vacuum assembly stack to track the mass of petroleum hydrocarbons volatilized and ensure compliance with the air-discharge permit.

The vast majority of hydrocarbon mass removed is in the liquid (free-product) phase when free product is being recovered. Free-product recovery rates have remained constant during the first year of operation; thus, monitoring of aqueous- and gaseous-phase hydrocarbons has been kept at the regulatory requirement minimum. The process monitoring program can be modified if needed.

Free-Phase Recovery

Full-scale startup of the bioslurper system was initiated on January 11, 1993. The system operates continuously with brief shutdowns for system maintenance and occasional site monitoring. For the first year the system operated for 6,556 hours, or approximately 39 weeks. Total free product recovered was 6,469 gal, an average rate of 24 gal/day. Figure 6 presents the first-year FPR data, when 45,859 (170 lb/day) hydrocarbons were removed from the site in the liquid phase (based on an assumed specific gravity of 0.85 for JP-5 fuel). Total groundwater recovered was 180,385 gal for an average extraction rate of 0.46 gpm. Figure 7 presents the first-year recovery data for fuel and groundwater. As the slopes of the two lines show, recovery rates have remained relatively constant through the first year of operation.

Aqueous-Phase Hydrocarbons

The mass of hydrocarbons removed in the aqueous phase was estimated based on the total volume of groundwater extracted and the average concentration of total petroleum hydrocarbons (TPH) found in

Bioslurper Aboveground Components

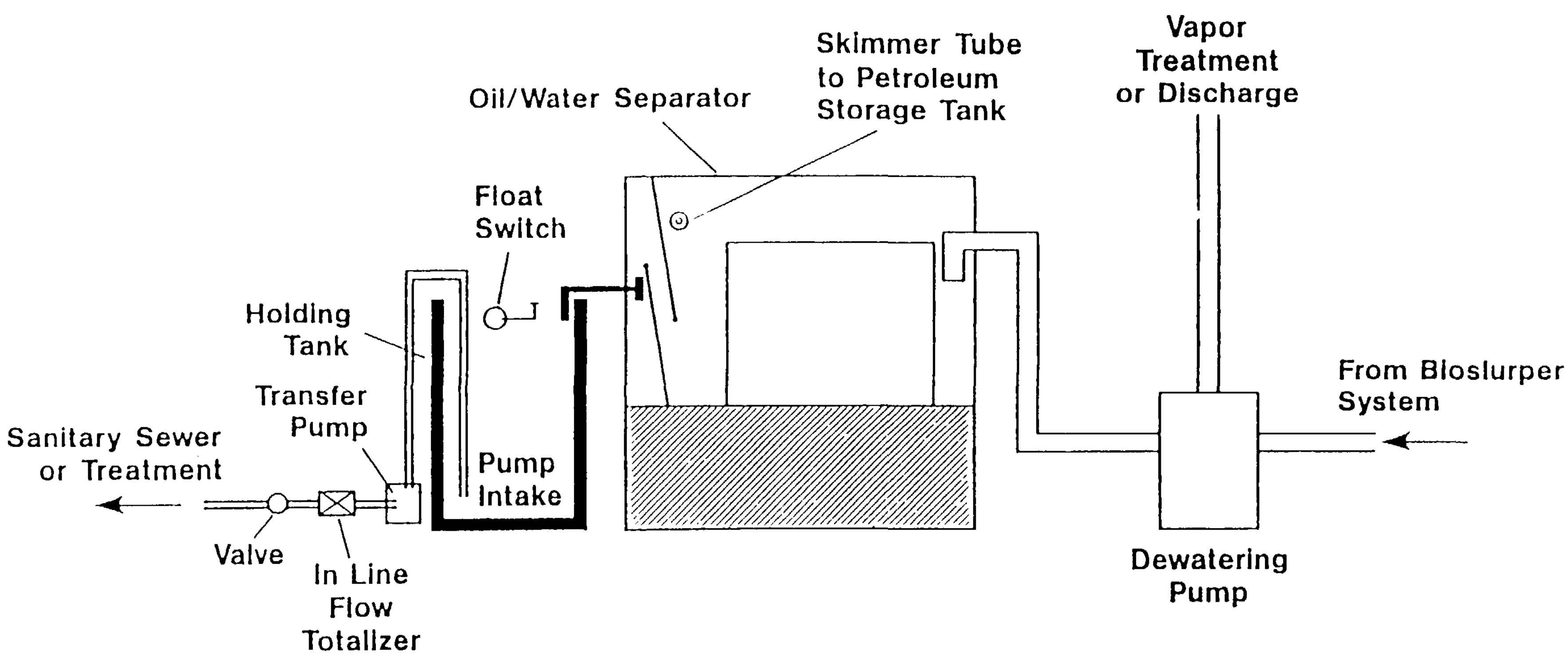

Figure 3. Diagram of Bioventing System Components

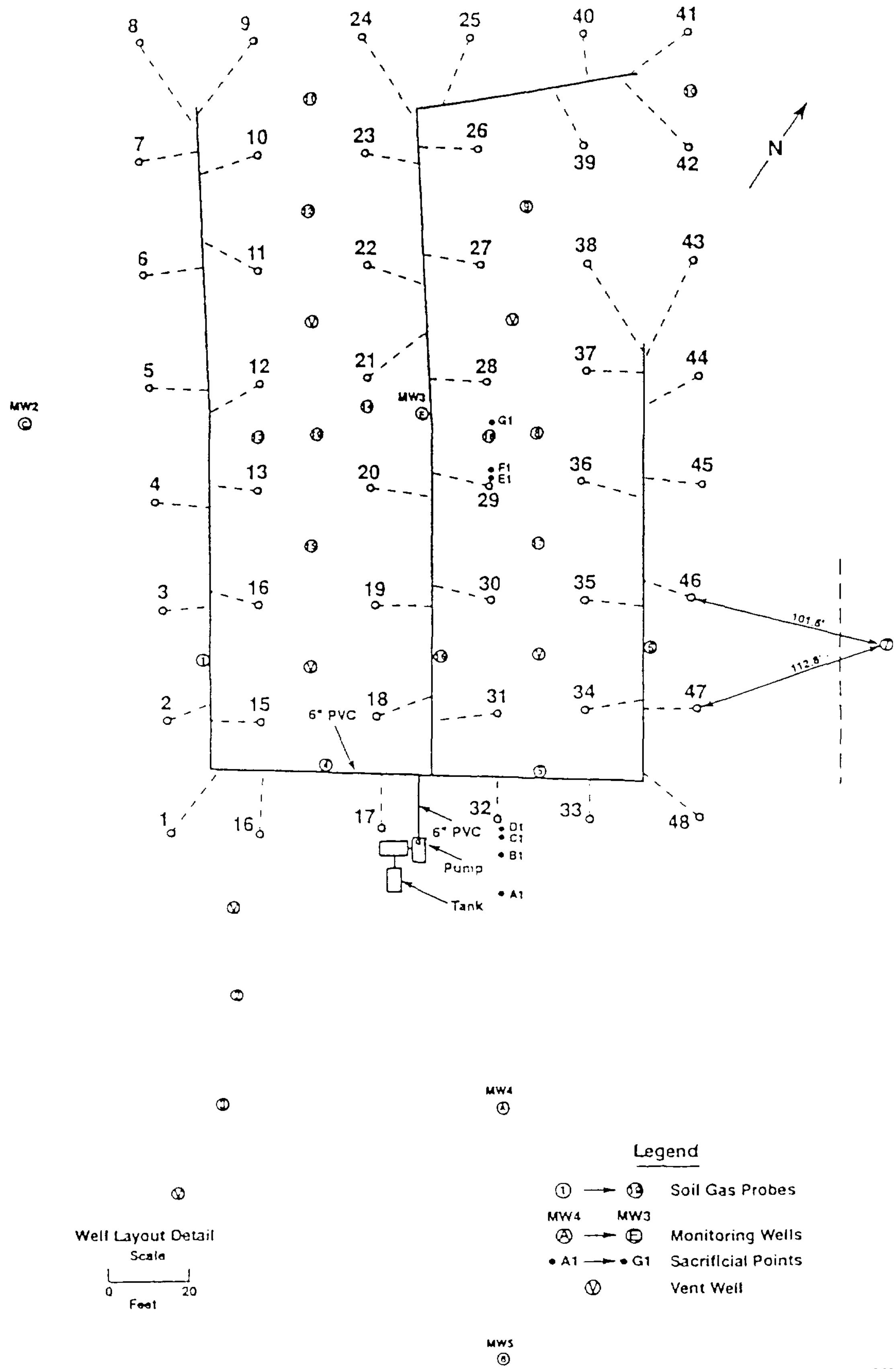

Figure 4. NAS Fallon Bioslurper Well Configuration

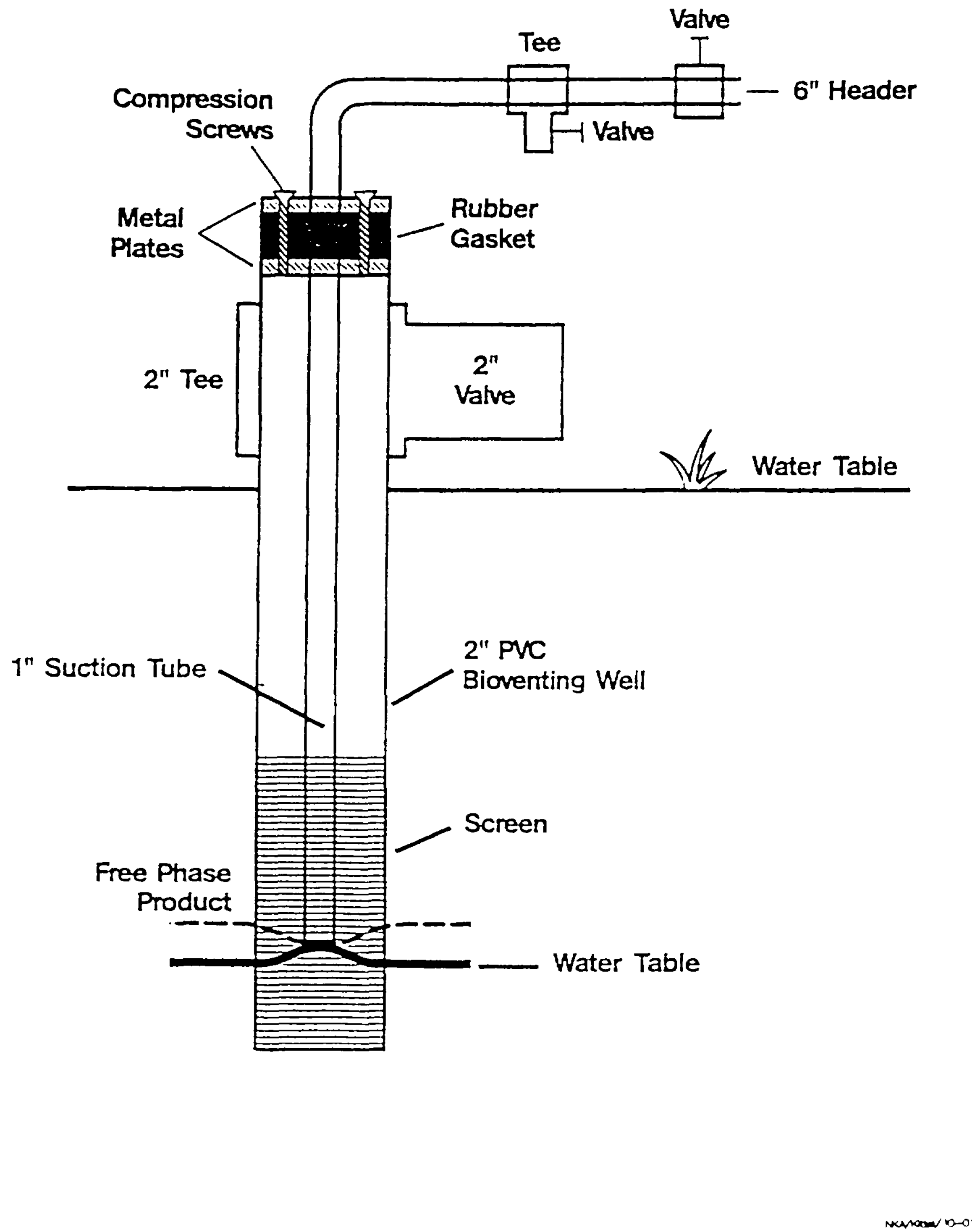

Figure 5. Bioslurper Well Design

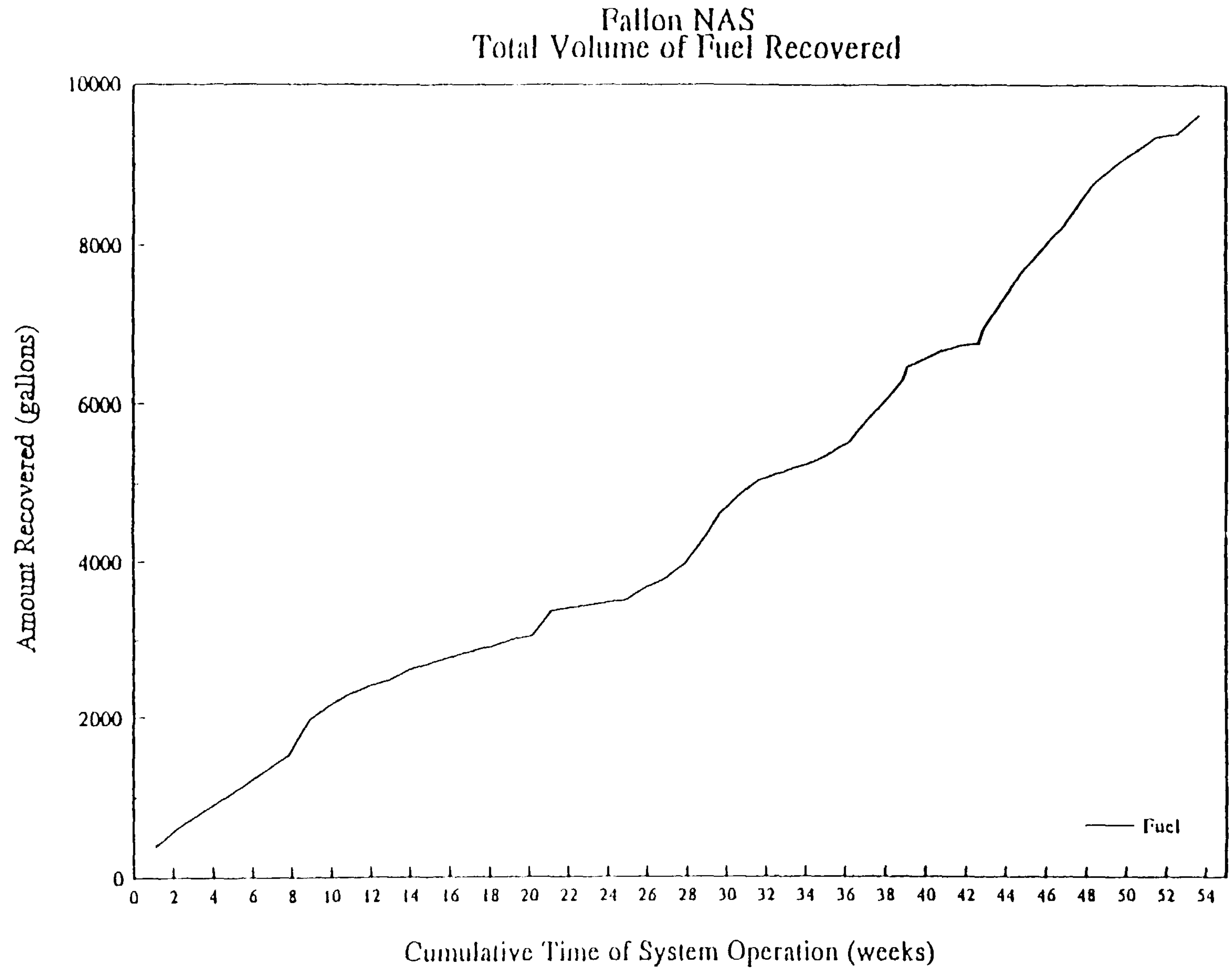

Figure 6. Cumulative Free-Product Recovery Data for the NAS Fallon Bioslurper System

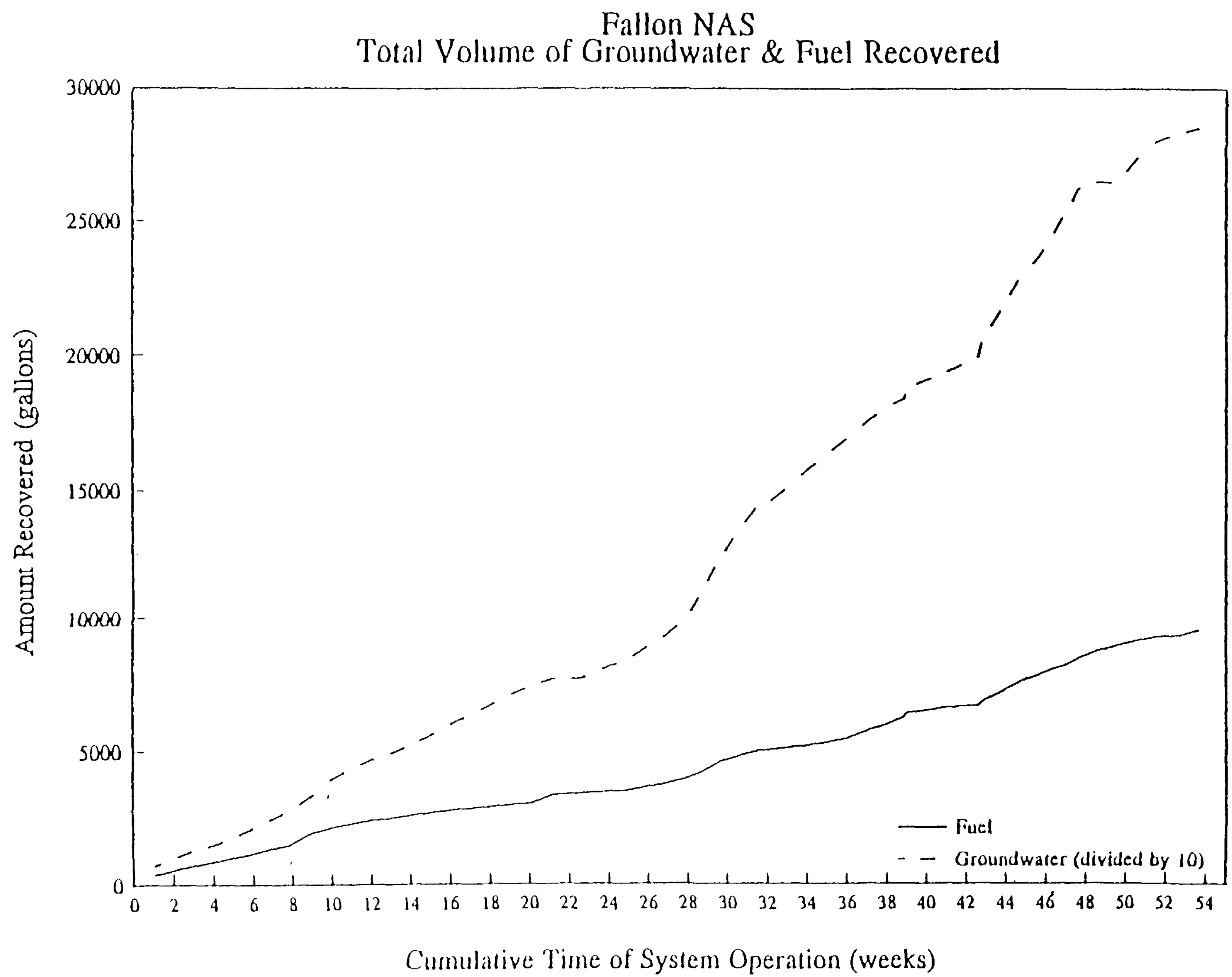

Figure 7. Cumulative Free-Product and Groundwater Extraction Volumes for NAS Fallon Bioslurper System

the monthly regulatory samples. By December 31, 1993, a total of 180,385 gal of groundwater had been extracted, with an average flowrate of 0.46 gpm; a total of 10 groundwater discharge samples were analyzed for TPH concentration (as JP-5) to quantify mass of hydrocarbons removed in the aqueous phase. Concentration values ranged from 30 mg/L (ppm) to 200 mg/L, with an average concentration of 104 mg/L. The estimated mass of hydrocarbons removed in the aqueous phase for the first year of operation was 157 pounds (71 kg), with an average rate of 0.58 lb/day.

Gaseous-Phase Hydrocarbons
The gaseous discharge was sampled several times to investigate the mass of hydrocarbons released to the atmosphere. The average measured emission concentration from the bioslurper was 1,300 mg/m^3. The average flowrate was 40.25 scfm, for a total of 15,622,635 ft^3 (438,046 m^3) soil gas extracted. The estimated mass of hydrocarbons discharged in the gaseous phase for the first year of operation was 1,256 pounds (569 kg), for an average discharge rate of 4.66 lb/day.

Total Hydrocarbons
The total estimated mass of hydrocarbons removed from the NAS Fallon bioslurper test site during the first year of operation is 47,272 lb. The percentage of mass removed in the liquid phase is 97.0%, in the dissolved phase 0.3%, and in the gaseous phase 2.7%. Table 1 summarizes the NAS Fallon hydrocarbon recovery data.

Table 1. Summary of Hydrocarbon Recovery Data for NAS Fallon Bioslurping System

Hydrocarbon Phase	Mass Removed (lb)	Percent of Mass Removed
Liquid (Free Phase)	45,859	97%
Aqueous	157	0.3%
Gaseous	1,256	2.7%
Total	47,272	100%

DISCUSSION

The premise of vacuum-assisted FPR is that the fuel recovery rate can be enhanced by inducing a gradient to the extraction wells via negative pressure. It follows that higher recovery rates should be achieved as system vacuum is increased. To investigate the relationship between recovery and vacuum, the system vacuum at the pump intake was recorded daily during the system maintenance check. This datum was plotted versus daily fuel recovery volume as shown in Figure 8. There is a positive correlation between increased vacuum and increased fuel recovery rates. The same relationship is evident for groundwater recovery versus system vacuum. Although the vacuum readings were taken only once per day and may not represent the average system vacuum during each daily recovery period, there are sufficient data points to reveal the general trend of the effect of vacuum on recovery rates.

The total system vacuum does not represent the vacuum being applied inside each well. The actual increase in hydraulic gradient to each well is equal to the vacuum that is translated to each wellhead and is affected by pressure drops in the system manifold and by the site soil permeability. System total vacuum has varied from 3.0 to 12.0 inches of **mercury** (3.4 to 13.6 ft of water). Measured wellhead vacuums have ranged from 15 to 30 inches of **water** vacuum. A 24-inch water vacuum at the wellhead would provide an equivalent hydraulic gradient increase to a 24-inch groundwater depression in a well. In the future, the use of a continuous pressure monitoring system will be

Fuel Recovery vs. System Vacuum

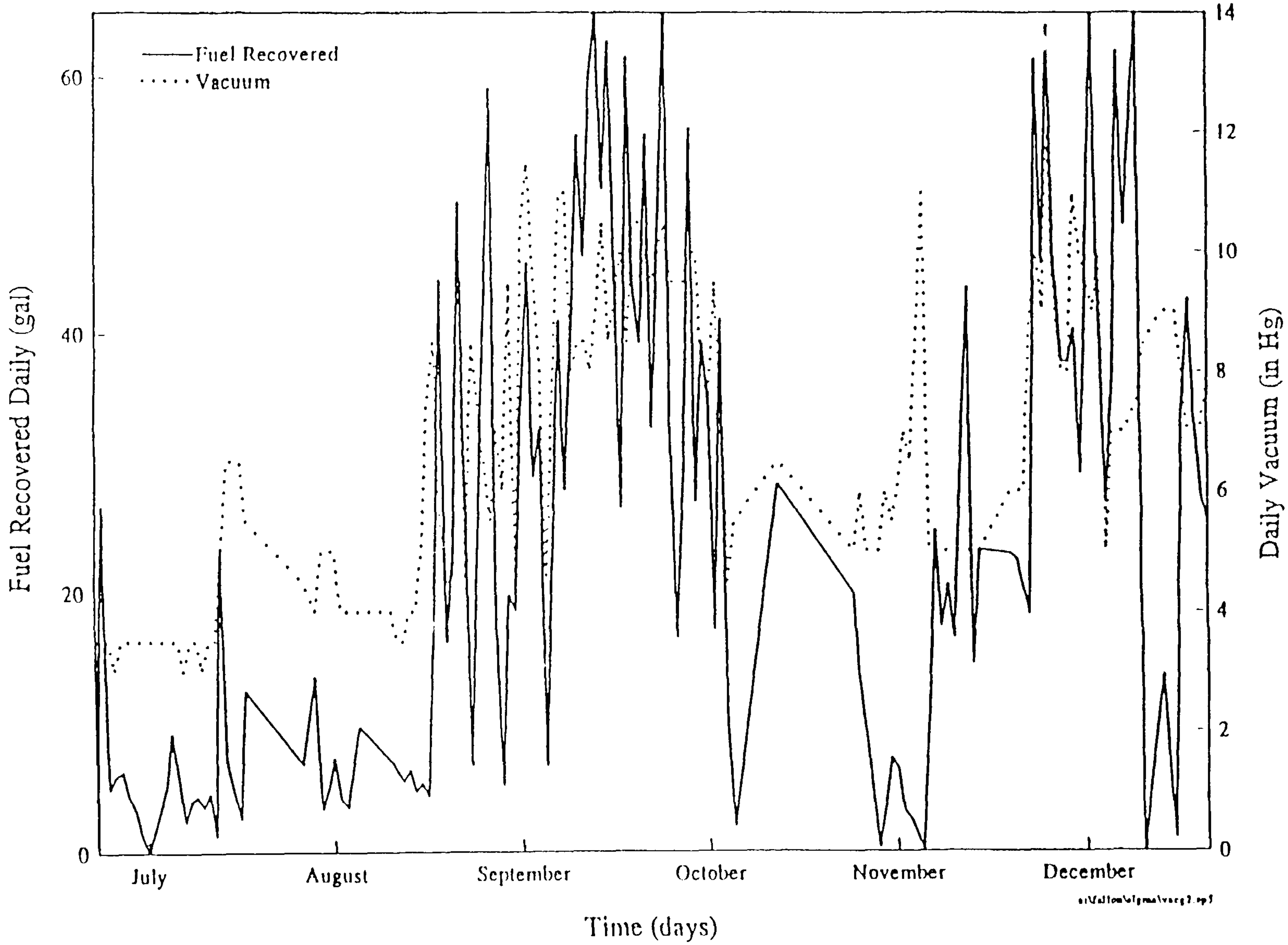

Figure 8. Graph of Bioslurper System Vacuum and Daily Free-Product Recovery

investigated to collect vacuum data from the manifold system and the wellheads to better observe the relationship between fuel recovery and vacuum.

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Jeffrey A. Kittel is a Program Manager at Battelle-Columbus Laboratories. Mr. Kittel has extensive experience managing and conducting field demonstrations of innovative technologies for petroleum contaminant remediation, including: bioventing, free product recovery, and soil vapor extraction. He is responsible for the design and installation of bioslurper and bioventing systems for Navy and Air Force field programs including the Fallon Bioslurper Field Demonstration, the Air Force Bioventing Initiative, and the Air Force Multi-Site Bioslurper Initiative. Mr. Kittel has 10 years experience in hazardous waste and petroleum contamination remediation research. He received his B.A. in Geology from Ohio Wesleyan University, and a B.S. in Chemistry from Otterbein College. Address: Battelle-Columbus Laboratories, 505 King Avenue, Columbus, Ohio 43201. Phone (614) 424-6122; FAX (614) 424-3667.

Robert E. Hinchee is a Senior Research Leader and Senior Program Director at Battelle-Columbus Laboratories. Dr. Hinchee has extensive experience in the development and application of technology to the assessment and remediation of contaminated sites. He has been involved in the development and application of new technologies including soil gas surveying, soil venting, in-situ bioremediation, and TCE cometabolic bioremediation at more than 200 sites throughout the United States. Dr. Hinchee is a professional engineer and received a Ph.D. in Civil and Environmental Engineering from Utah State University. Battelle-Columbus Laboratories, 505 King Ave., Columbus, Ohio 43201-2693, (614) 424-4698.

Ron Hoeppel is a Environmental Engineer and Senior Soil Microbiologist at the Naval Facilities Engineering Service Center in Port Hueneme, California. Mr. Hoeppel is responsible for conducting research for the Navy's Installation Restoration Program which investigates cost effective and innovative technologies for site remediation. He is the project director for the Navy's Fallon Bioslurper Field Demonstration and the Multi-Site Bioventing Demonstration at the Marine Corps Air Ground Combat Center in Twentynine Palms, California. Mr. Hoeppel received his B.S. in Geology from Cal Polytechnic State University and his M.S. in Soil Microbiology from New Mexico State University. Address: Naval Facilities Engineering Service Center, Port Hueneme, California, 93043. Phone (805) 982-1655; FAX (805) 982-1409.

Ross N. Miller, Ph.D., P.E., CIH is a Lt. Colonel and a Senior Bioenvironmental Engineer, and Chief of the Technology Transfer Division at the USAF Center for Environmental Excellence, Brooks AFB, Texas. He holds a Ph.D. in Civil and Environmental Engineering from Utah State University and has managed Occupational Health and Environmental Protection Programs at two major Air Force installations. He is currently responsible for the technical direction of remedial actions at multiple Air Force installations and specializes in fuel spill remediation using bioventing and other innovative technologies. Center for Environmental Excellence, 8001 Arnold Drive, Brooks AFB, Texas 78235-5000.

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Sixth National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods

May 11 - 13, 1992
Riviera Hotel
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Abstract

The 1992 Outdoor Action Conference was comprised of 3 days of technical presentations, workshops, demonstrations, and an exhibition.

A total of 60 papers were presented at the meeting.

Sessions were devoted to the following topics:

Vadose Zone Monitoring Technology
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THE USE OF IN-SITU "DUAL" VACUUM EXTRACTION FOR REMEDIATION OF SOIL AND GROUNDWATER

Bretton E. Trowbridge, P.E.

Terra Vac Corporation
Costa Mesa, California

David E. Ott

Terra Vac Corporation
Costa Mesa, California

I. ABSTRACT

"Dual Extraction" provides a rapid and cost-effective method of remediating soil and groundwater impacted by volatile organic compounds (VOC's). Dual Extraction is the removal of both water and vapors through the same borehole by use of entrainment. This technology provides for the remediation of the vadose zone, capillary fringe, smear zone, and existing water table. The effectiveness of this technology is shown in a case study.

A release from an Underground Storage Tank (UST) was responsible for a hydrocarbon plume spreading over approximately 50,000 square feet. The release produced vadose zone contamination in the silty and sandy clays from 10 - 30 feet below ground surface (bgs) with TPH concentrations up to 1,400 mg/kg. In addition, a layer of free floating liquid hydrocarbon was present on a shallow aquifer located at 30 feet bgs in thicknesses ranging from 0.5 feet to 3.0 feet.

An in-situ dual-extraction system was installed to remediate the soils and groundwater to levels as required by the Los Angeles Regional Water Quality Control Board (RWQCB). The system operated 24 hours/day for 196 days with an operating efficiency of over 99%. After 196 days (28 weeks), over 17,000 pounds of hydrocarbons had been extracted from the soils.

Seven confirmatory soil borings were advanced in the area of highest initial hydrocarbon concentrations and indicated that TPH and BTEX concentrations had decreased over 99% from initial soil concentrations. Three confirmatory groundwater samples were obtained from monitoring wells initially exhibiting up to 3 feet of floating product. Confirmatory samples exhibited non-detectable (ND) concentrations of TPH and BTEX. Based upon the positive confirmatory results, site closure was obtained from the RWQCB in May of 1991.

In only 28 weeks of operation, the groundwater contamination was reduced from free floating product to non-detectable concentrations of TPH by the use of Dual Vacuum Extraction.

II. DUAL VACUUM EXTRACTION - AN OVERVIEW

Dual Vacuum Extraction is a synergistic process, combining vacuum extraction with groundwater extraction to remove both vapors and water from the same well. This in-situ, physical treatment recovers contaminants existing in liquid, vapor, and dissolved phases from the subsurface.

A. Vacuum Extraction

Vacuum Extraction, although a relatively new technology, has gained widespread acceptance and use in the past few years. It is a relatively inexpensive and quick method of removing Volatile Organic Compounds (VOCs) from the subsurface.

These VOCs exist in the subsurface in one of four possible phases[1]:

- Residual liquid phase VOCs, located within the soil matrix, floating on the water table, or sinking through the water table.
- Vapor phase VOCs residing in the soil matrix
- VOCs dissolved in the soil moisture and groundwater
- VOCs adsorbed onto the soil particles

Vacuum Extraction removes the VOCs by inducing a negative pressure gradient in the soil matrix. The lower pressure causes the liquid VOCs to vaporize. The vapor phase VOCs are drawn towards the extraction well via the air flow caused by the induced vacuum, then brought to the surface and treated. The effectiveness of this process is dependent on several site-specific parameters, including the properties of the contaminant (especially Henry's Law Constant, vapor pressure, and solubility), the subsurface conditions (permeability, moisture content, porosity), and system parameters (well spacing, well vacuum, well flow rate)[1] .

Typically, the zone of effectiveness for vacuum extraction is limited vertically by the boundary of the saturated zone and the vadose zone. At this boundary, the high water content in the pore spaces causes a significant number of the diffusion pathways to be blocked[2]. Vapor diffusion becomes limited by aqueous-phase transport through the blocked pores. The boundary of the saturated zone is typically where high concentration of VOCs are found, due to the migration patterns of the VOCs in the subsurface, as illustrated by Figure 1[2]. These high concentrations typically extend down into the capillary fringe to the water table.

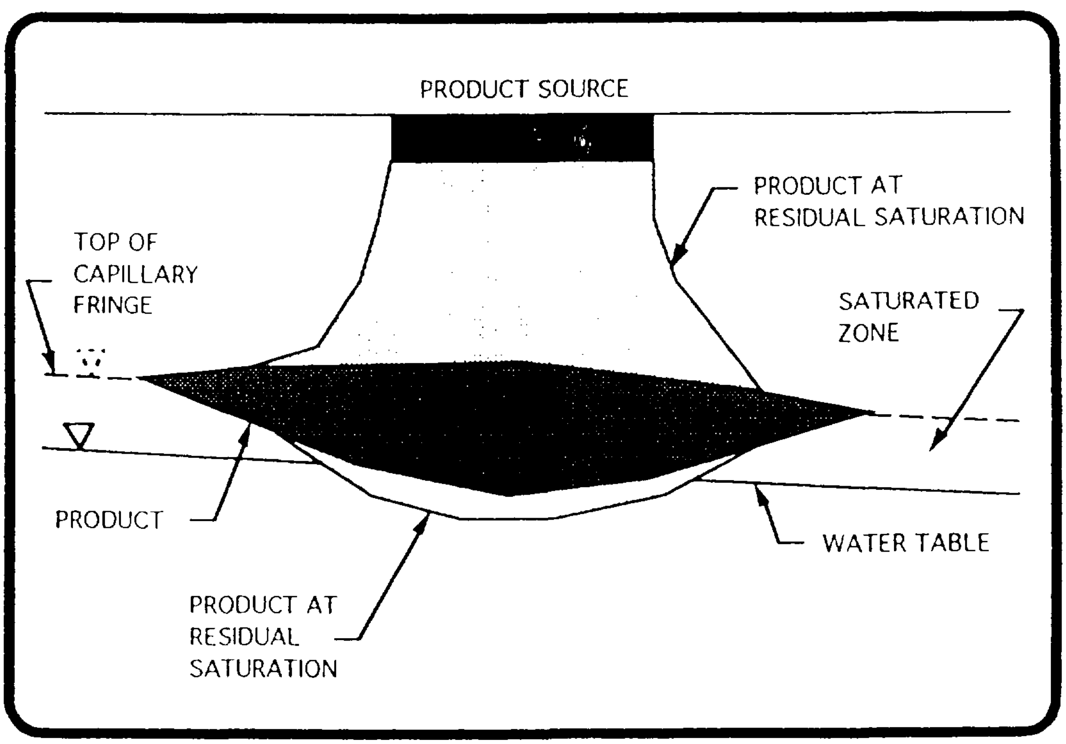

FIGURE 1: HYDROCARBONS IN THE SUBSURFACE

The inability of vacuum extraction to treat this high concentration saturated zone is a major limitation of the technology.

B. Groundwater Extraction

Groundwater pump-and-treat is probably the best-known and most often used method of groundwater remediation and aquifer restoration. However, recent experiences have shown that several major inefficiencies exist with the pump-and-treat method.

When liquid VOCs are released on the surface, they percolate downward due to gravity forces and flushing action from precipitation. During this process, residual liquid phase VOCs are retained in the unsaturated zone due to capillary and adsorptive forces. Up to 55% of the pore volume of the soil may be occupied by residual VOCs[3]. Pump and treat methods are unable to clean up these residual VOCs directly. As additional precipitation occurs, small amounts of these residuals are dissolved and flushed into the groundwater, representing a continuing source of contamination.

With a significant release of a VOC which is less dense than water, a pool of liquid VOC may form on top of the water table. As the water table fluctuates in height due to seasonal or tidal variations, this pool will 'smear' the soil within it's area of fluctuation, as shown in Figure 2. If the water table rises, residual VOC becomes trapped within the saturated zone, creating yet another continuing source of dissolved phase VOCs. If the water table falls, the pool of liquid VOC will also fall, leaving behind a residual of VOC in the newly created unsaturated zone[2] . Pump and treat methods are unable to address this 'smear' zone effectively.

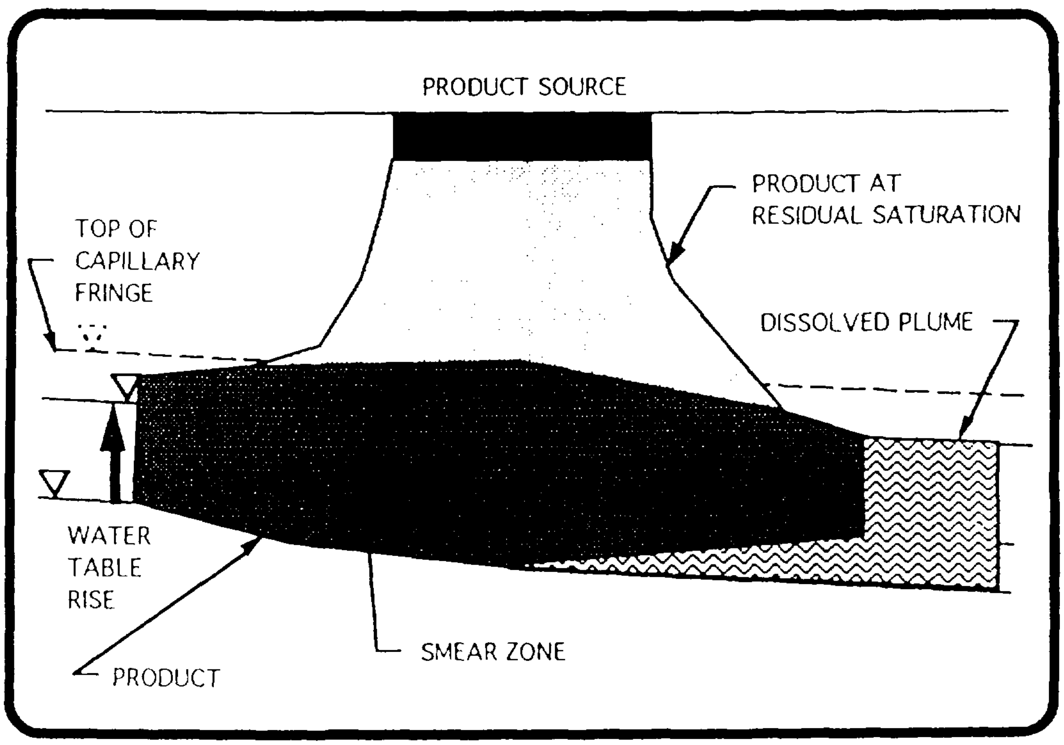

FIGURE 2: SMEAR ZONE FORMATION

C. Dual Vacuum Extraction

Dual Vacuum Extraction synergistically combines the attributes of vacuum extraction and groundwater extraction. The process is able to:

- Recover residual VOCs below the static water table, where vacuum extraction is typically not applicable.
- Recover VOCs from within the cone of depression created by pumping of the aquifer, where pump-and-treat is normally not effective.
- Increase the water extraction rates in low permeability settings, thereby increasing the well capture zone.
- In certain low permeability settings, eliminate the use of downhole pumps entirely through the use of entrainment extraction.

Dual Vacuum Extraction effectively remediates the 'smear zone' by the combined use of vapor and water extraction. The static water table is lowered by water extraction. This opens up the 'smear zone' in the formerly saturated area to the air flow induced by the applied vacuum, as shown in Figure 3. The smear zone is then quickly remediated.

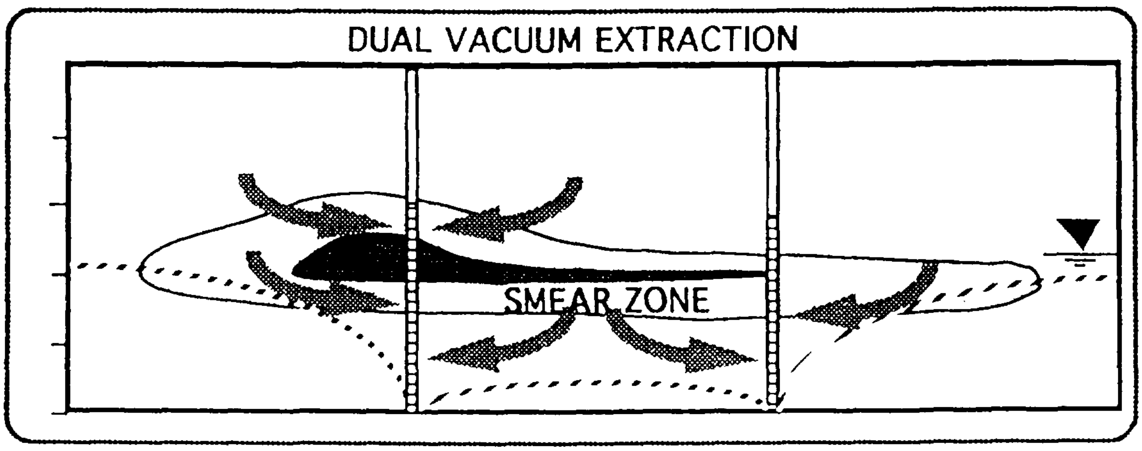

FIGURE 3: DUAL VACUUM FXTRACTION REMEDIATION

During Dual Vacuum Extraction operations, groundwater recovery rates are significantly greater than conventional pumping methods due to the negative pressure gradient in the well vicinity. The negative pressure gradient helps overcome the capillary forces which tend to hold the water trapped in the soil voids. This increased pumping rate causes a larger drawdown in the well, and thereby extends the capture zone of the well[3].

In some low permeability aquifers, down-hole pumps can be eliminated entirely. Instead of electric or pnuematic down-hole pumps, an entrainment system is used to entrain the water in the extracted air. Thus, a single vacuum header only is run to each well. This header transports both the vapors and entrained water to a water/vapor separator. In the separator, the extracted water is drawn off and treated, typically by carbon adsorption. The vapors continue on via a different path to be treated by carbon adsorption, catalytic oxidation, or other means. A typical dual vacuum extraction process flow diagram is shown in Figure 4.

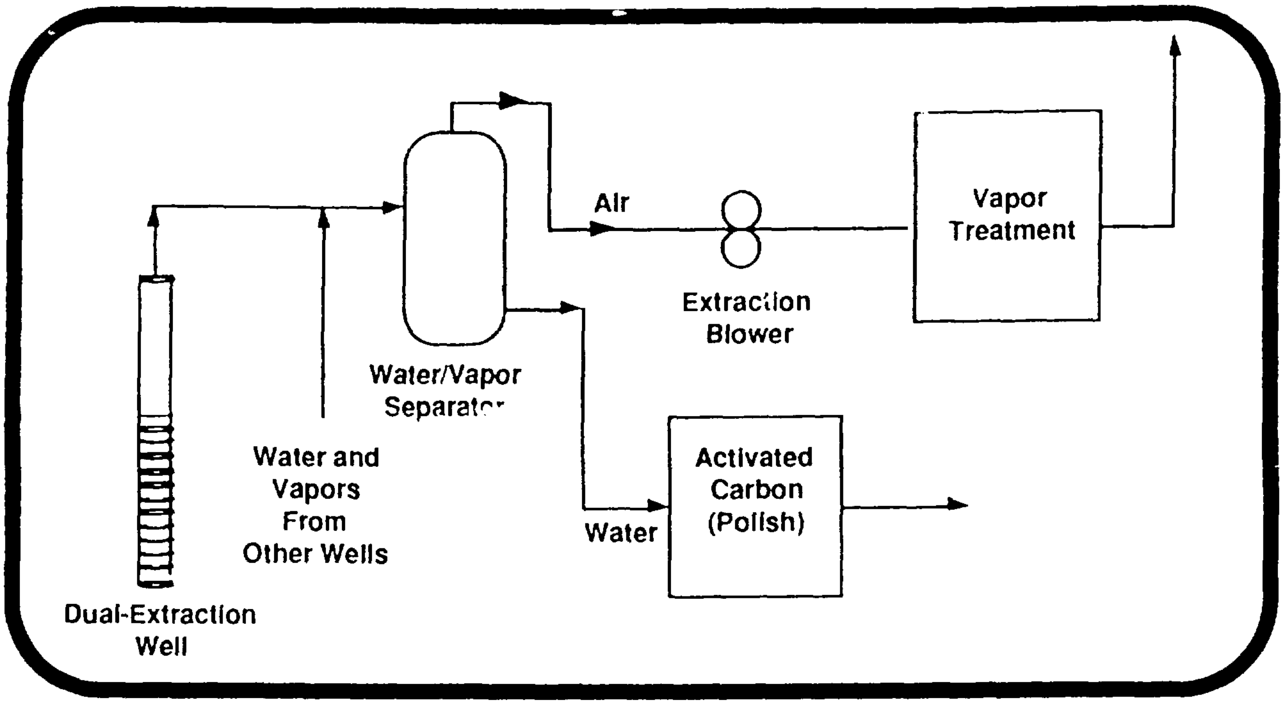

FIGURE 4: TYPICAL DVE PROCESS FLOW

The savings obtained by not installing down hole pumps and their associated control systems can be significant. System operation is greatly simplified.

In addition, most of the volatile organic compounds are removed from the extracted water during the entraining and transport process. (In effect, the entrainment system is acting like an air stripper). Because of this, VOC concentrations in the water entering the water treatment systems are much lower than would otherwise be expected. Substantial savings in carbon regeneration costs have been realized because of this.

Dual Vacuum Extraction is effective and applicable in the following circumstances:

- Sites with VOCs in both the soils and groundwater.
- Sites with fluctuating groundwater levels, where a 'smear zone' has been created.
- Sites with low permeability aquifers where extraction rates can be significantly increased, and entrainment extraction can reduce loading on the groundwater treatment system.

III. CASE STUDY--FORMER RENTAL CAR LOT, LOS ANGELES

Dual Vacuum Extraction was successfully used to remediate both the soils and groundwater at a former rental car lot in Los Angeles. Initial conditions included up to three feet of liquid phase gasoline residing on the water table. Regulatory closure was obtained in only 28 weeks of operation.

A. Site Description

1. Site History and Background

The site was used as a rental car lot for approximately twenty years. Two ten-thousand gallon underground storage tanks were utilized to dispense gasoline to the cars. Development of the site as a portion of an office complex was planned; therefore, site assessment was initiated. Preliminary investigations revealed the presence of hydrocarbons in the soils and groundwater. Shortly thereafter, the underground storage tanks were removed. Additional site investigation was conducted to further delineate the hydrocarbon plume.

2. Geological Conditions

The site, located in the Los Angeles Basin, is underlain by soils of Recent alluvial silts and clays. The soils were generally moist and fractured.

The soils from the surface to approximately 50 feet below the surface consisted of brown silty clay. Petrophysical analyses of these soils indicated that the soils are of low permeability, approximately 0.1 milli-Darcy. Results are presented in table 1 below.

TABLE 1: SOIL PETROPHYSICAL DATA

Sample Depth	Porosity %	K_v mDarcy	K_h mDarcy	Saturation %
20'	49.2	0.071	0.076	100.0
30'	54.2	0.340	0.100	99.4
30'	50.0	0.041	0.188	100.0
35'	54.0	0.058	0.062	99.2

*K_v = Native State Vertical Permeability to Air, in milliDarcy
*K_h = Native State Horizontal Permeability to Air,in milliDarcy

Perched groundwater was encountered in most borings at 25 to 30 feet below the surface. The perched groundwater zone was created by the tighter clays present at the site. The regional aquifer is located at an approximate depth of 220 feet below the surface.

3. Hydrocarbon Impaction

The various subsurface investigations conducted at this site revealed gasoline-range hydrocarbon impaction ranging in depth from 10 to 35 feet below the surface. A sample cross section showing the extent of the hydrocarbons is presented in Figure 5. The hydrocarbon-impacted soil covered an area approximately 280 feet by 450 feet.

The highest concentration of gasoline-range hydrocarbons found was 1400 mg/Kg, located in the center of the lot at a depth of 15 feet below the surface. The average concentration of gasoline-range hydrocarbons was approximately 100 mg/Kg.

The perched groundwater located at approximately 25 to 30 feet below the surface was also significantly impacted by hydrocarbons. The monitoring wells on site prior to the remediation contained from 6 to 36 inches of floating liquid product.

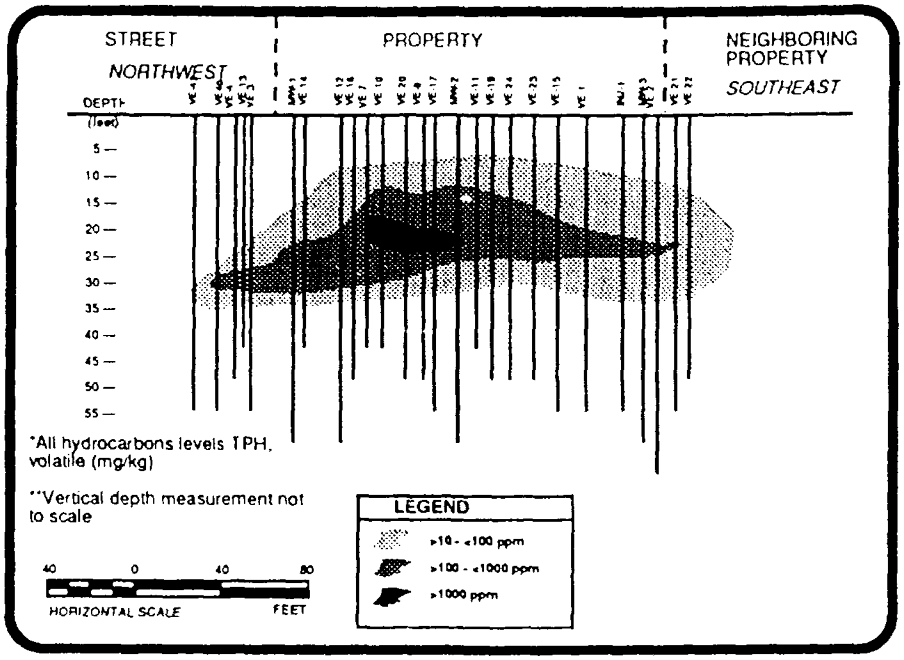

FIGURE 5: HYDROCARBON PLUME CROSS-SECTION

B. Dual Extraction System Description

1. Dual Extraction Wells

The system initially consisted of twenty-nine dual extraction wells. These wells were typically screened from 20 to 35 feet below the surface, with some screened intervals extending up to 10 feet below the surface, and others extending down to 50 feet below the surface. The screened intervals were selected based on two criteria. The first criterion was that the screen must be placed so that the saturated zone could be fully de-watered using dual extraction. The second criterion was that the screen interval must adequately remediate the areas of highest hydrocarbon concentrations, as measured by organic vapor monitor readings taken during drilling. A well spacing of approximately 40 feet was utilized, with closer spacings used in areas of high hydrocarbon concentration to speed the remediation process.

The well field was expanded twice, to address hydrocarbons that had migrated off-site. Thirteen additional dual extraction wells were installed to the north-east of the site, and four additional dual extraction wells were installed to the west of the site in the adjacent street. The final system comprised a total of forty-six dual extraction wells. A site map showing the final well locations in relation to the hydrocarbon plume is presented in Figure 6.

Water was extracted from each well using air entrainment. The combined vapor/water mixture was extracted under vacuum and brought to the treatment system.

2. Remediation Equipment

Vapor and water treatment equipment utilized for the site included a water/vapor separator, two vacuum extraction blowers, a catalytic oxidizer for vapor treatment, a surge tank for the extracted water, and two carbon adsorption vessels connected in series. Treated water was discharged to the local sewer system initially, then to a nearby storm drain. A process flow diagram is presented in Figure 7.

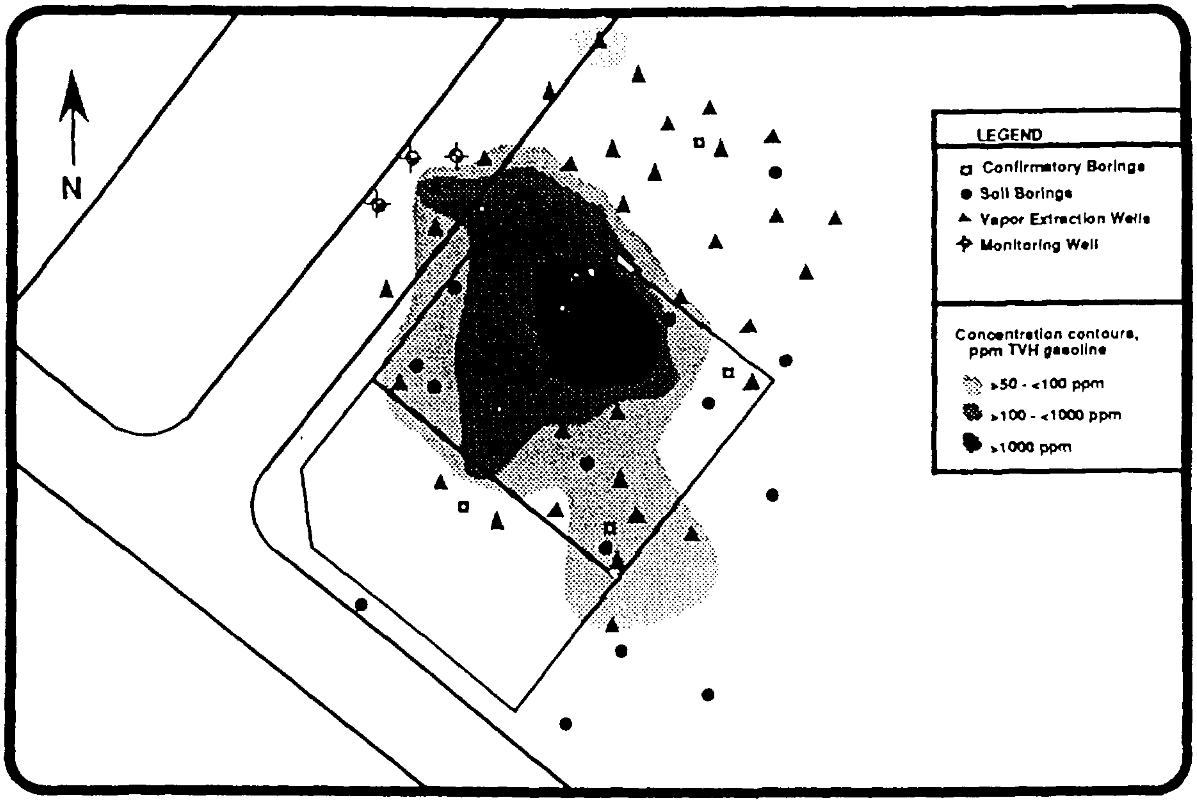

FIGURE 6: SITE PLAN VIEW

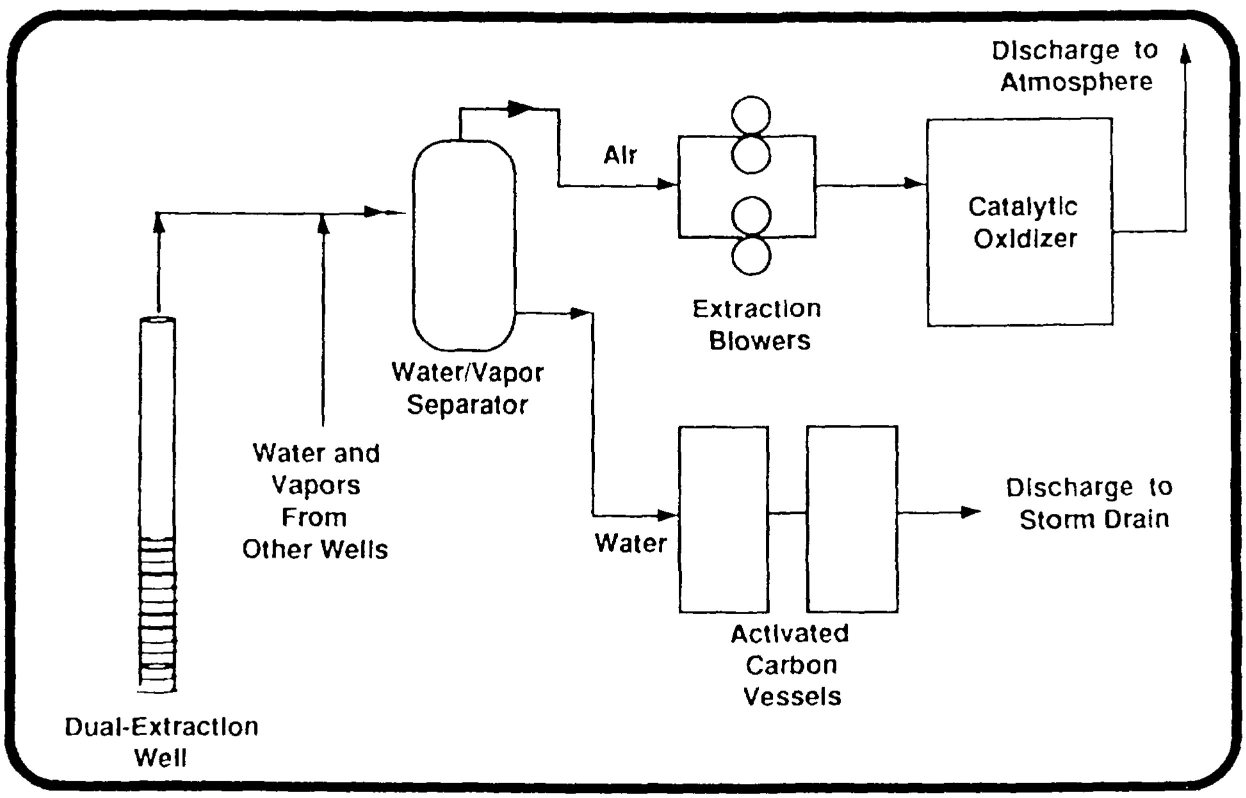

FIGURE 7: SITE SYSTEM DIAGRAM

The blowers utilized were 40 horsepower, positive displacement blowers capable of a combined flow of 1000 standard cubic feet per minute (SCFM) at an inlet vacuum of 15 inches of mercury (Hg). The catalytic oxidizer was capable of treating up to 1000 SCFM of vapors with a destruction efficiency of 99.8%, and was capable of destroying up to 960 pounds of VOCs per day. The carbon adsorbtion vessels held 1000 pounds of carbon each, and were rated for a maximum flow of 50 gallons per minute each.

3. Operations

The system operated for a total of twenty-eight (28) weeks, with an operational efficiency of over 99%. System flow rate averaged nearly 1000 SCFM for the life of the project. An average flow rate of 20 SCFM from each well was obtained at a wellhead vacuum of 10" Hg. Measured radii of influence were in excess of twenty (20) feet. Over 17,000 pounds of VOCs were removed from the soils, equivalent to more than 2,600 gallons of gasoline. Figure 8 presents the cumulative pounds of VOCs removed versus run time. As shown below, system extraction rates decreased over 99%.

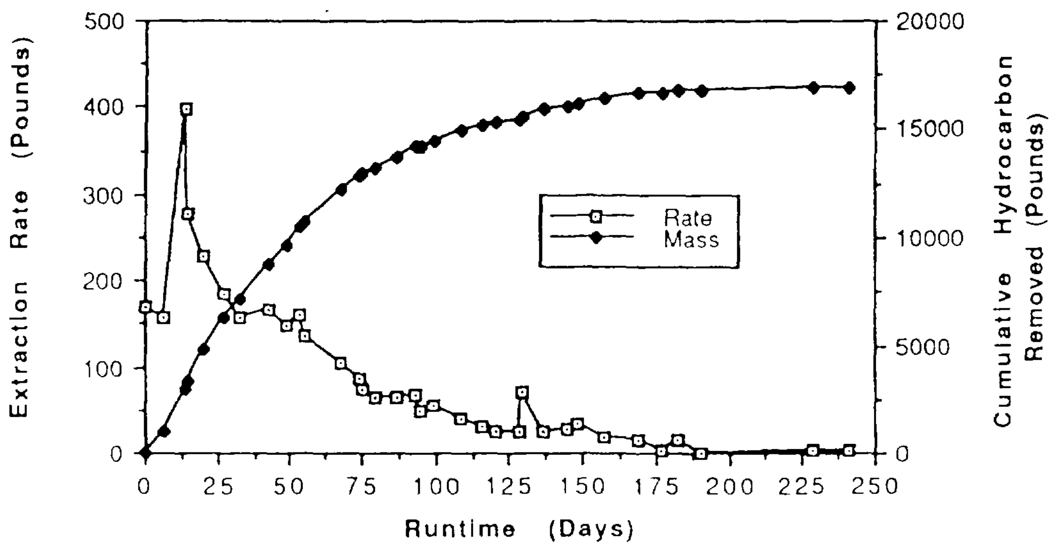

FIGURE 8: HYDROCARBON REMOVAL VERSUS RUN TIME

Over the 28 weeks of operations, 89,000 gallons of groundwater had been extracted and treated. After 10 weeks of operations measured groundwater levels were an average of 5 feet lower than before operations began, demonstrating the effectiveness of using entrainment extraction for de-watering the saturated zones.

4. Effectiveness of Remediation

A confirmatory soil boring program was undertaken with lead agency approval, consisting of advancing seven borings to a total depth of 40 feet, with laboratory analysis of samples taken every five feet. Seventy-five percent of the samples had non-detectable levels of benzene; the average concentration of benzene in the remaining twenty-five percent of the samples was 0.17 mg/Kg. Total Volatile Hydrocarbons (TVH) were not detected in seventy-one percent of the samples; of the remaining twenty-nine percent, the average concentration of TVH was 10.7 mg/Kg. The following table compares soil sample results from two confirmatory borings with the sample results from nearby initial borings at corresponding depths.

TABLE 2: CONFIRMATORY BORING RESULTS COMPARISONS

Comparison #1	Initial Concentration (mg/Kg)	Final Concentration (mg/Kg)
TVH	1400	ND
Benzene	3.9	ND
Toluene	33	ND
Ethylbenzene	17	ND
Xylene	94	ND
Comparison #2		
TVH	300	12
Benzene	3.7	0.006
Toluene	20	0.010
Ethylbenzene	5.2	0.066
Xylene	38	0.440

As part of the closure program, three groundwater samples were taken to assess the remediation effect upon the groundwater. The wells that were sampled originally contained up to three feet of floating liquid hydrocarbon. These samples were analyzed for TVH and the gasoline constituents benzene, toluene, ethylbenzene, and total xylenes (BTEX). All constituents were non-detectable. Table 3 below illustrates the progress of remediation as measured by two of the monitoring wells.

TABLE 3: GROUNDWATER REMEDIATION PROGRESS

Well MW-4

Compound	Week 0 ug/L	Week 12 ug/L	Week 22 ug/L	Week 28 ug/L
Benzene	FP*	5	ND	ND
Toluene	FP*	ND	ND	ND
Ethylbenzene	FP*	ND	ND	ND
Total Xylenes	FP*	22	ND	ND

* Free Product, approximately 24" thick on water table

Well MW-1

Compound	Week 0 ug/L	Week 26 ug/L	Week 28 ug/L
TVH	FP**	160	ND
Benzene	FP**	11	ND
Toluene	FP**	2	ND
Ethylbenzene	FP**	1	ND
Total Xylenes	FP**	26	ND

** Free Product, approximately 36" thick on water table

IV. CONCLUSION

As shown by the case study presented above, Dual Vacuum Extraction can be an effective method of rapidly remediating both soils and groundwater simultaneously. Although limited by certain site-specific factors, Dual Vacuum Extraction can be applied to a wide variety of sites, with lithologies varying from sands to clays. The most significant limitations to Dual Vacuum Extraction are the same as apply to conventional vacuum extraction; these are contaminant volatility and soil permeability. However, Dual Vacuum Extraction can significantly decrease the time required for in-situ remediation of site soils and groundwater. Because of the reduced operating time, and the elimination of a requirement for down-hole pumps, Dual Vacuum Extraction can significantly reduce the total expenditure required. Finally, Dual Vacuum Extraction is effective at remediating aquifers with very low permeabilities, such as silts and clays.

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[1] Malot, James J., and Trowbridge, B.E., "Soil Remediation and Free Product Removal using In-situ Vacuum Extraction with Catalytic Oxidation", Fourth National Outdoor Action Conference on Aquifer Restoration, Groundwater Monitoring and Geophysical Methods, May 1990.

[2] Johnson, Dr. R.L., "Leaking Underground Storage Tanks", Titan Press, 1990.

[3] Malot, James J., P.E, and Piniewski, Robert, "Innovative Technology for Simultaneous In Situ Remediation of Soil and Groundwater"

THE EFFECT OF SOIL CHARACTERISTICS ON FREE-PHASE HYDROCARBON RECOVERY RATES

G.D. Beckett[1] and David Huntley[2]

ABSTRACT

Light nonaqueous phase liquid (LNAPL) saturation and movement in the subsurface are controlled by capillary pressure and the capillary characteristics of the soil. Where free-product occurs in monitoring wells, hydrocarbon saturations in the formation vary significantly as a function of the observed thickness in the monitoring well and the soil texture. Fine-grained soils generally exhibit lower LNAPL saturations than coarse-grained material for the same observed thickness in a monitoring well. Because the relative permeability of soil toward LNAPL decreases with decreasing saturation, and because the intrinsic permeability of fine-grained soils is less than that of coarse-grained soils, free product pumping or skimming have less likelihood of success in fine-grained soil. Further, for any soil type, recovery decreases LNAPL saturation near the well, with the effect diminishing with distance. Therefore, a zone of decreased permeability will be formed around LNAPL recovery wells, further retarding recovery from greater distances.

MAGNAS3 (Huyakorn et al., 1992), a three-dimensional, finite-element model that can simulate movement of three active phases (air, water, and LNAPL), was used to investigate LNAPL recovery in three different soil types. Recovery in fine-grained soils was limited, with significant reductions in LNAPL saturation occurring only within about 10 to 15 feet of the well. Recovery of LNAPL in coarse-grained soils was predicted to be much more successful, with approximately 95% percent of the original hydrocarbon recovered through fluid pumping. The analysis further suggests that increases in the hydraulic recovery rate (i.e., not considering volatilization) can be realized in all of the soils studied through vacuum enhanced free product recovery (VEFR). Other potential strategies for optimizing the recovery of free-product are discussed. VER

INTRODUCTION

Light nonaqueous phase liquids (LNAPL) such as gasoline, fuel oil, and a host of other products, are sometimes released to the subsurface. Many contain compounds that can adversely affect human and environmental health. Therefore, it has been the general practice of health regulators to require the cleanup of free phase LNAPL at sites where it has been observed in monitoring wells. However, free product recovery by fluid pumping has had limited success at completely remediating sites. For instance, in downtown San Diego, an LNAPL pool known as the "blob" displays hydrocarbon thicknesses in observation wells up to 10 feet. The plume is estimated to have an approximate volume of 64,000 gallons (Huntley et al, 1991). However, after three years of fluid recovery operations, less than a thousand gallons has been collected by the fluid recovery pilot system.

There are several theoretical reasons supporting these field observations. First, even if an appreciable thickness of free product is present in an observation well, the soil saturation may be small resulting in limited LNAPL mobility and recovery. Second, as fluid recovery proceeds, the area near the recovery well experiences the greatest reduction in hydrocarbon saturation. This leads to a reduction in relative permeability to LNAPL in that region, effectively forming a zone that inhibits hydrocarbon recovery from greater distances. Lastly, some LNAPL recovery systems are operated ineffectively.

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[1] Aqui-Ver, Inc., 11839 Sorrento Valley Rd, San Diego, California, 92121

[2] Department of Geological Sciences, San Diego State University, San Diego, California, 92182

LNAPL movement and recovery are strongly soil type dependent. The mechanics of some skimming and LNAPL cleanup systems do not allow the control necessary for optimum free product recovery.

The objectives of this study are to: 1) Investigate and quantify how soil type affects hydrocarbon recovery rate and ultimate effectiveness; 2) Consider and enumerate the physical limitations to LNAPL recovery; and 3) Quantify the effects of applying a vacuum to the LNAPL recovery system. Consideration of other LNAPL mass removal mechanisms, such as mass partitioning and biodegradation, are not within the scope of this study. However, as will be apparent at the conclusion of this article, other mass removal mechanisms will exceed LNAPL hydraulic recovery at some point in time for most soils.

THEORETICAL DEVELOPMENT

Petroleum engineers have long been aware that it is more difficult to remove oil (LNAPL) from reservoirs in the presence of water. Until recently, this was not generally considered relevant in contaminant hydrology because LNAPL was thought to float as a distinct layer on the capillary fringe (Blake and Hall, 1984) and flow into an observation well by gravity drainage. Since LNAPL flowing into a well would depress the water level within the well, it followed that the observed LNAPL thickness was exaggerated compared to the formation. Fine-grained soils with a large capillary fringe were thought to exhibit greater LNAPL exaggerations than coarse-grained soils with small capillary fringes.

As field and laboratory investigations continued, the preceding LNAPL conceptual model was shown to be inaccurate. Farr et al (1990) and Lenhard and Parker (1990), using multiphase fluid theory, simultaneously published papers showing that hydrocarbon and water coexist in the pores from the oil/water interface up to and slightly above the oil/air interface in the monitoring well (Figure 1). The relative saturations of water, LNAPL, and air in the formation were shown to depend on the observed thickness of LNAPL, the height above the oil/water interface in a monitoring well, fluid properties, and soil capillary characteristics. Recent field comparisons between predicted and measured hydrocarbon saturations and mobility (Huntley et al., 1994) strongly support these theoretical models. This work implies that the idea of an exaggerated thickness of LNAPL is erroneous. If the system is in vertical equilibrium, the LNAPL thickness observed in a monitoring well is equivalent to the thickness of soil affected by the free product. This thickness does not include a small LNAPL capillary fringe, or potentially over- or underlying residual

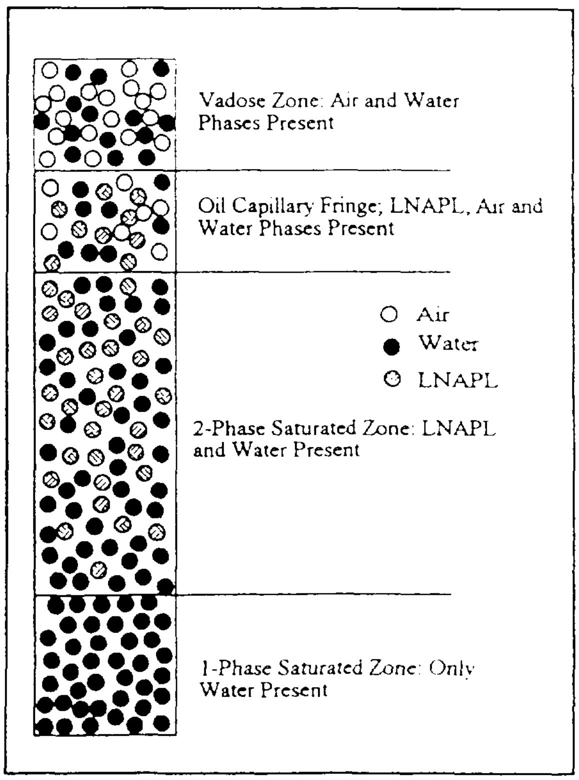


Figure 1. Schematic representation of pore saturation at vertical equilibrium (after Farr et al., 1990)

hydrocarbon stranded as a function of release history or ground water level variations. However, because some of the pore space between the oil/water interface and the oil/air interface is occupied by water (Figure 1), particularly in fine-grained soil, the true volume of formational hydrocarbon can be substantially less than that suggested by the observed thickness. This *volume* exaggeration can lead to overestimation in situ LNAPL, and set unrealistic precedents for site closure goals.

MATHEMATICAL DEVELOPMENT

Flow in the subsurface can be represented by Darcy's Law, generalized for multiphase flow (1) (Parker, 1989).

$$q_{pi} = -\frac{k_{rp} k_{ij}}{\mu_p}\left[\frac{\partial P_p}{\partial \chi_j} + \rho_p g \frac{\partial z}{\partial \chi_j}\right] \tag{1}$$

Where *i* and *j* are direction indices with repeated values indicating tensor notation, p is an index indicating fluid phase, q_{pi} is the Darcy velocity, k_{rp} is the relative permeability scalar, k_{ij} is the intrinsic permeability tensor of the soil, μ_p is viscosity, P_p is the pressure, ρ_p is the density, g is gravitational acceleration, z is elevation.

The intrinsic fluid, soil, and physical parameters above are derived by standard methods, or assumed from literature values. The relative permeability of the soil to water (w), LNAPL (l), and air (a) can be calculated by (2), which indicates relative permeability varies with phase saturation (Mualem, 1976a; Parker, 1989).

$$k_{rw} = S_w^{1/2}\,[1-(1-S_w^{1/m})^m]^2 \tag{2a}$$

$$k_{rl} = (S_t - S_w)^{1/2}\,[\,(1-S_w^{1/m})^m - (1-S_t^{1/m})^m\,]^2 \tag{2b}$$

$$k_{ra}\ (1-S_t)^{1/2}\,(1-S_t^{1/m})^{2m} \tag{2c}$$

Where S_w is the effective water phase saturation, S_t is the effective total fluid saturation (water and LNAPL), m is a soil capillary parameter (van Genuchten, 1980). The saturation of any phase in the pore space is a function of the capillary pressure (Parker, 1989), as described by equation (3).

$$P_c = P_{nw} - P_w \tag{3}$$

Where P_c is the capillary pressure, P_{nw} is the pressure of the nonwetting phase and P_w is the pressure of the wetting phase. Three capillary pressure couplets can be described with the wetting sequence defined as water, followed by LNAPL, followed by air. Van Genuchten (1980), describes a continuous function (4) relating capillary head to moisture content in a water-air system.

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1+(\alpha h)^n]^m} \qquad (4)$$

Where θ is volumetric moisture content, θ_s is the saturated moisture content, θ_r is the residual moisture content, h is capillary pressure head, alpha and n are soil-type and fluid dependent capillary parameters, and m = 1-1/n. In a three-phase system, the capillary parameters must be measured separately for each fluid pair and soil type (i.e., water-LNAPL, water-air, air-LNAPL), or more conveniently, scaled from one couplet (usually water-air) to all others in the system using the ratios of interfacial fluid tensions (Parker, 1989).

After converting moisture content to saturation, equations 1 through 4 can be linked to describe LNAPL movement in a three-phase system (water, LNAPL, air). This set of equations is highly nonlinear, necessitating solution by numerical approximation. MAGNAS3 (1993) is a program that can provide the desired solutions for the preceding multiphase relationships. The code has been extensively benchmarked by the authors, and verified accurate against both analytic equations and experimental data (Huyakorn et al., 1994; Panday et al., 1994). It should be noted that hysteresis, emulsion, and other more complicated aspects of soil and fluid physics are not considered.

STUDY APPROACH

Three soil types, typical of the categories ML, SM, and SW in the Unified Soil Classification System (USCS), were selected for study in context with LNAPL recovery. The USCS system is widely used by earth scientists and engineers to designate soil types. A specific soil representing each of these classes was selected from a catalog containing necessary physical information (Mualem, 1976b), such as porosity, permeability, and capillarity (Table 1); invariant fluid and physical parameters used in the simulations are provided in Tables 2 and 3. The ML selected was a silt loam that contained approximately 16% clay, 54% silt, and the remainder fine- to very coarse-grained sand. The SM was a sandy loam that contained approximately 9% clay, 26% silt, and the remainder fine- to very coarse-grained sand. The SW was a clean, well-graded sand containing about 35% very fine- to fine-grained sand, with the remainder comprised of medium- to very coarse-grained sand. Since soil hydraulic properties can vary widely within any USCS designation, the results of this study are comparative. Site specific parameters are required to evaluate LNAPL recovery schemes for any particular project.

MAGNAS3 (1992) was used to simulate the vertical and radial distribution of LNAPL in a radially symmetric domain for each of the test cases evaluated (to be discussed in detail subsequently). The radial domain cross-dimensions are 15 by 57.5 meters, with the original water table (before LNAPL loading) at approximately 10 meters (Figure 2). The model grid is finely discretised near the recovery well and in the zone of LNAPL saturation. Vertical grid dimensions are as small as 10 centimeters (cm), with the radial dimension starting at 5 cm and expanding outward. The resulting grid is 31 x 50 for a total of 1550 nodes.

The water-phase boundary condition was assumed to be constant pressure, resulting in no ground water drawdown at the distal model boundary. Given the relatively small drawdowns at the recovery well, little error is introduced from this condition. The distal LNAPL boundary is no-flow, approximating a free product lens of finite volume. The LNAPL recovery well conditions were modeled using constant pressure boundaries for each appropriate phase (water, LNAPL, air), similar to conditions imposed by many commercially utilized cleanup systems.

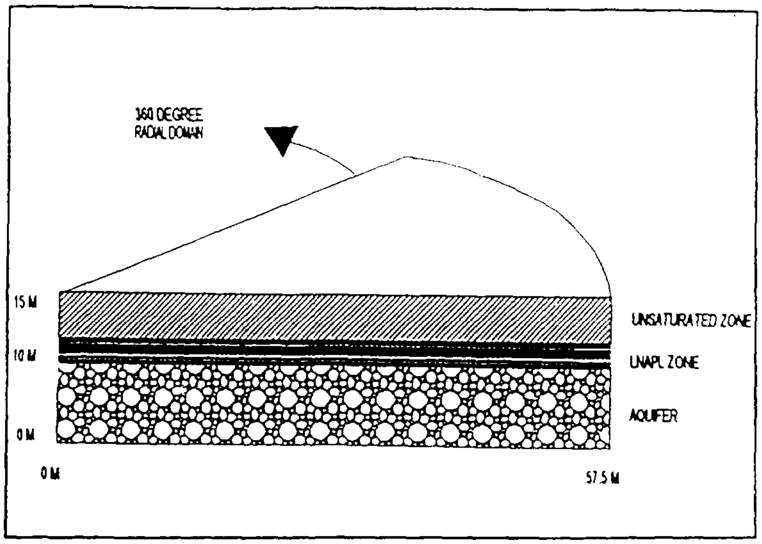


Figure 2. Radial model domain used for simulations. The piezometric surface (corrected water table) is at 10 m elevation.

Thirteen simulations were performed to evaluate various aspects of LNAPL recovery. The model domain was identical for each case, with specific parameters varied to quantify their effects on recovery. The initial portion of the study evaluates fluid recovery (LNAPL and water) through time in three different isotropic soils using simple hydrocarbon skimming aided by groundwater pumping from the recovery well. Each soil was modeled to have an LNAPL saturation profile such that 3.05 m (10 ft) of free product would be observed in a monitoring well before pumping (Figure 3).

The groundwater drawdown for these first simulations was approximately 2.3 meters (7.5 feet), resulting in a lowering of the groundwater piezometric surface to the static oil/water interface in the well. This drawdown was selected to affect only the portion of the saturated zone containing both LNAPL and water (Figure 3). The corresponding hydrocarbon drawdown was 3.05 m (10 ft), also resulting in lowering the oil/air interface in the well to the original oil/water interface. The second set of simulations is identical to the first, except that a 10:1 horizontal to vertical permeability anisotropy was added.

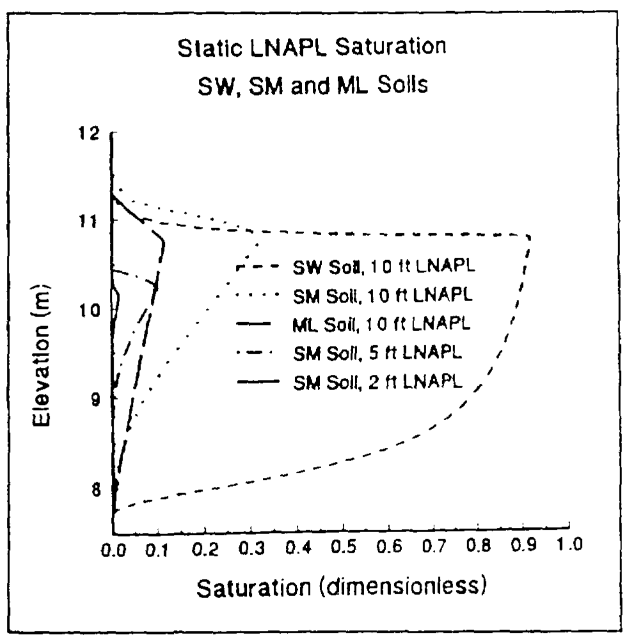


Figure 3. Initial hydrocarbon saturations used in simulations, based on vertical equilibrium.

The third set of simulations consisted of two evaluations considering different initial hydrocarbon saturations, the first corresponding to two feet of observed thickness in a monitoring well, the second to five feet. These simulations were both conducted only for the intermediate soil type (SM). The purpose of these runs was to compare potential differences in ultimate mass removal percentages as a function of initial conditions.

Table 1. Soil Parameters Used in Simulations.

PARAMETER	SOIL 1: ML	SOIL 2: SM	SOIL 3: SW
Permeability (m^2)	1.78e-13	3.21e-13	1.54e-11
Porosity	0.441	0.381	0.305
Van Genuchten "α" (m^{-1})	0.67	0.9	7.34
Van Genuchten "n"	1.325	2.29	2.27
Residual Moisture (est'd)	5.00e-03	5.00e-03	5.00e-03

Table 2. Intrinsic Properties Used for All Simulations

Property	Water	LNAPL	Air
Density (kg/m^3)	1000	750	1.22
Dynamic Viscosity (Pa· s)	0.00105	0.0006	0.000018

Table 3. Interfacial Tension

Fluid Pair	Interfacial Tension (dynes/cm)
Air/Water	75
LNAPL/Water	51.7
Air/LNAPL	23.4

The fourth set of simulations evaluated the effects of varying groundwater drawdown on total free product recovery, also in the SM soil. In all cases the oil/water interface in the well during recovery was simulated to be coincident with the oil/water interface.

The last portion of the study considers the effect of applied vacuum to LNAPL recovery. Many field studies and the authors' personal experience have suggested that applied vacuum increases free product recovery (VEFR). However, we are not aware of any studies that quantify the method from a physical standpoint. Two isotropic simulations were performed for the SM and SW soil types with the vacuum applied in the capillary fringe and below the water table.

RESULTS

Effects of Soil Type on Simple Skimming

Soil type exhibited the strongest control on the effectiveness of hydrocarbon recovery of all of the variables considered, including the amount of groundwater drawdown and the use of enhanced remediation technologies. Although 10 ft of hydrocarbon was assumed to exist in the production well at the beginning of recovery for all of the soil types, this 10 ft of hydrocarbon corresponds to widely varying hydrocarbon saturations (Figure 3) and volumes (Table 4). Peak saturations under hydrostatic equilibrium (the initial condition) for the SW soil approach 90% (e.g. 90% of the pore space is filled with LNAPL, 10% is filled with water). The initial LNAPL volume in the full 57.5 m simulation domain for the SW soil was 1.9 million gallons (Table 4). In contrast, peak saturations in the SM soil were about 30%, with an initial volume of 0.5 million gallons. The finer ML soil resulted with peak saturations of only 11% and a total volume of 0.25 million gallons. These variations in saturations from soil to soil, due primarily to capillary properties, result in lower relative LNAPL permeability in the fine-grained soils. This low relative permeability, coupled with lower intrinsic permeability (Equation 1), results in very limited LNAPL mobility and subsequent recovery in fine-grained soil.

Simple hydrocarbon skimming, aided by groundwater production to lower the piezometric surface, can be very effective in coarse grained soils, such as the SW soil used for our simulations. Ninety six percent of the hydrocarbon is predicted to be removed from the full problem domain (57.5 m in radius), and 98% of the hydrocarbon is predicted to be removed from the limited domain close (within 5 m) to the well (Table 4). Hydrocarbon saturations are reduced from peak values of 90% to saturations less than 20% near (within 1.3 m) the well (Figure 4). Initial recovery rates from the skimming well are predicted to exceed 10 gallons per minute (gpm), decreasing to less than 1 gpm after three years of skimming as saturations decrease, resulting in decreased hydraulic conductivity and transmissivity (Figures 5, 6).

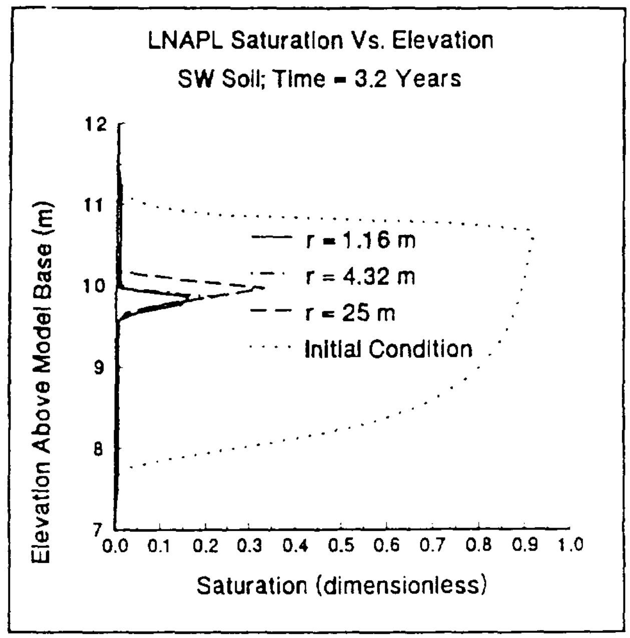


Figure 4. Hydrocarbon saturations as a function of elevation and distance from skimming well after 3.2 yrs of recovery, SW soil.

As discussed previously, initial hydrocarbon saturations within the SM soil are substantially less than in the SW soil, resulting in decreased hydrocarbon mobility. The total hydrocarbon volume in the 57.5 m model domain for the SM soil was calculated to be about one-fourth that in the SW soil (Table 4). Peak hydrocarbon saturations of 30% in the SM soil are predicted to decrease to about 10% near the well (within 1 m) after 3.2 years of skimming (Figure 7). Though the model indicates that 46% of the hydrocarbon found within 5 meters of the well would be recovered after 3.2 years, only about five percent of the total hydrocarbon found within the 57.5 m model domain was predicted to be recovered (Table 4). Initial LNAPL recovery rates are predicted to be about 0.06 gpm, decreasing rapidly to rates of less than 0.02 gpm (Figure 8).

The ML soil has the least amount of hydrocarbon within the pore space under the initial conditions (Table 4). The total domain contains only 252,000 gallons of hydrocarbon, of which only 18,000 gallons are predicted to be recovered after 3.2 years of recovery. Initial peak saturations of about

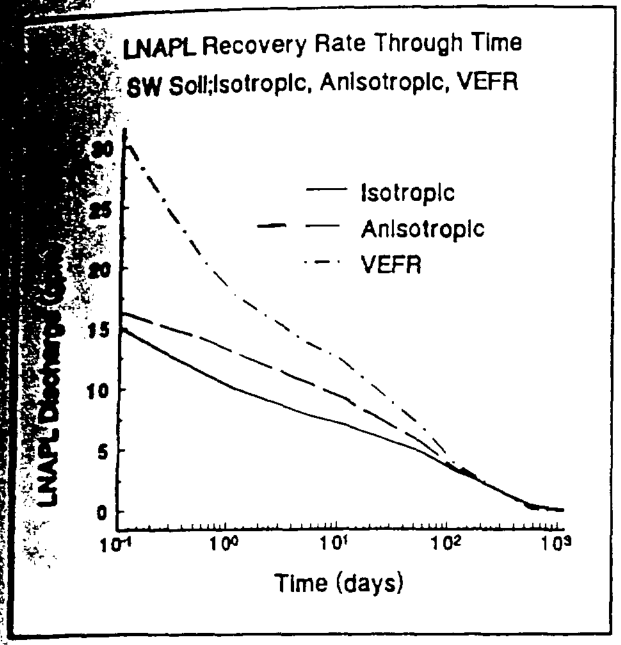


Figure 5. Predicted LNAPL recovery rates with **time**, SW soil.

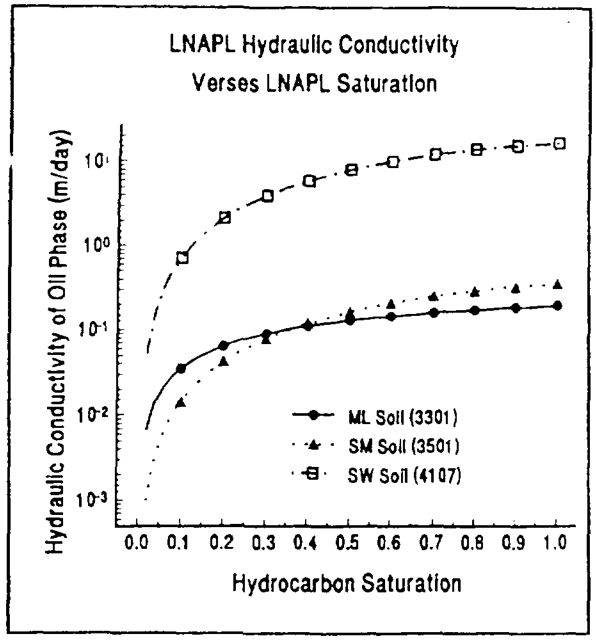


Figure 6. Hydraulic conductivity of LNAPL as a function of LNAPL saturation for SW, SM, and ML soils (air saturation = 0).

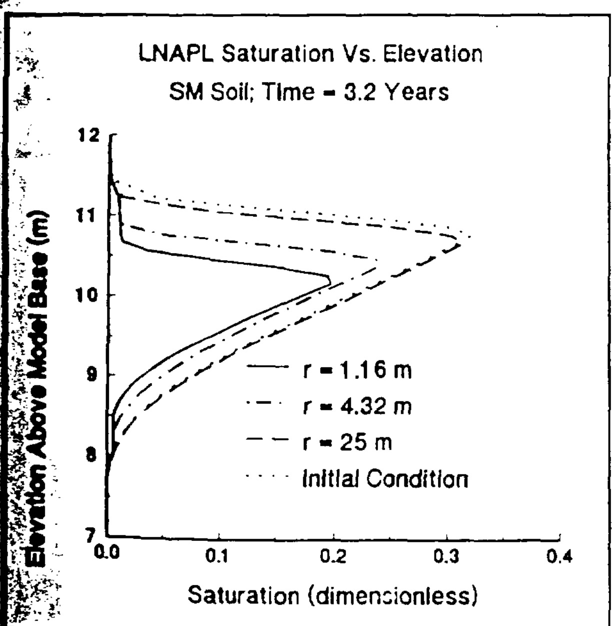


Figure 7. LNAPL saturations as a function of **elevation** and distance from the recovery well **after** 3.2 yrs of skimming, SM soil.

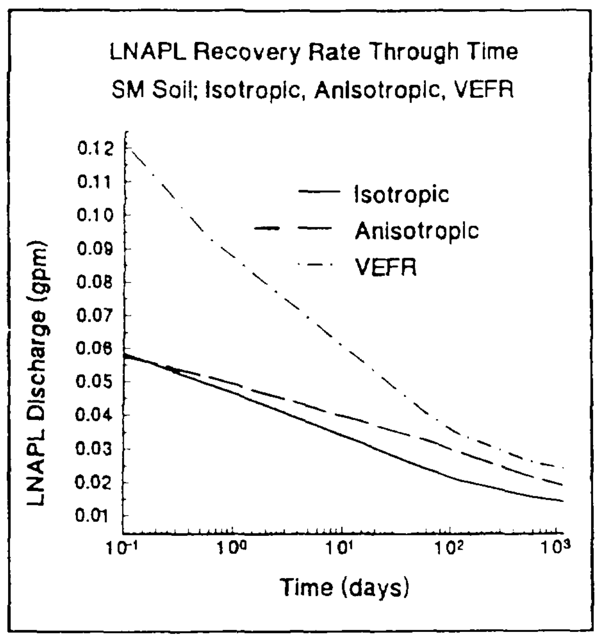
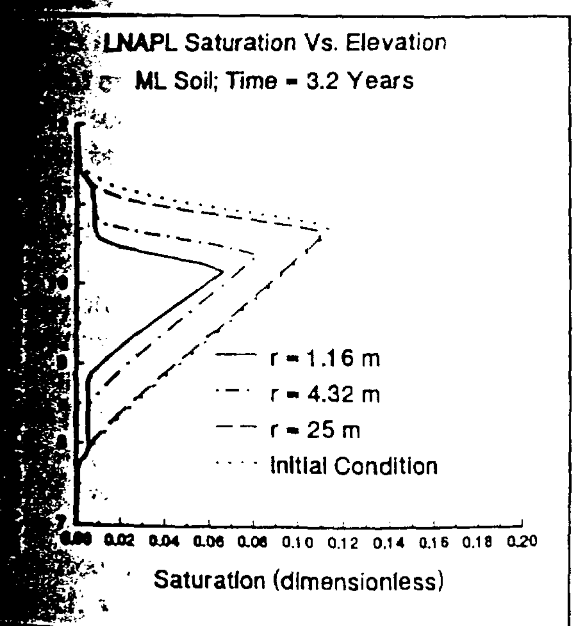


Figure 8. Predicted LNAPL recovery rates as a function of time, SM soil.

Table 4. Effectiveness of hydrocarbon skimming for three soil.

	Full Domain (57.5 m radius Area)			Limited Domain (5 m radius Area)		
	Hydrocarbon Volume (thousands of gallons)		Percent Recovery	Hydrocarbon Volume (thousands of gallons)		Percent Recovery
	Initial	After 3.2 yrs		Initial	After 3.2 yrs	
Isotropic	1,920	81	96	14.4	0.35	98
Anisotropic		61	97		0.3	98
Isotropic	504	476	5.5	3.74	2.01	46
Anisotropic		465	7.7		2.1	43
Isotropic	252	234	7.1	1.87	0.86	54
Anisotropic		232	7.8		1.2	36

...are reduced to approximately 6% after 3.2 years of recovery at distances in excess of one meter ...the well (Figure 9). Recovery rates start out at about 0.03 gpm (43 gallons/day), and decrease ...to 0.01 gpm (14 gpd) (Figure 10). For both the SM and ML soil types, significant decreases ...hydrocarbon saturation were limited to a relatively small area around the production well. ...Hydrocarbon saturations 25 m from the production well were virtually unchanged after 3.2 years of ...ing in these soils (Figures 7, 9).



...9. LNAPL saturations as a function of ...on and distance from the recovery well ...3.2 yrs of skimming, ML soil.

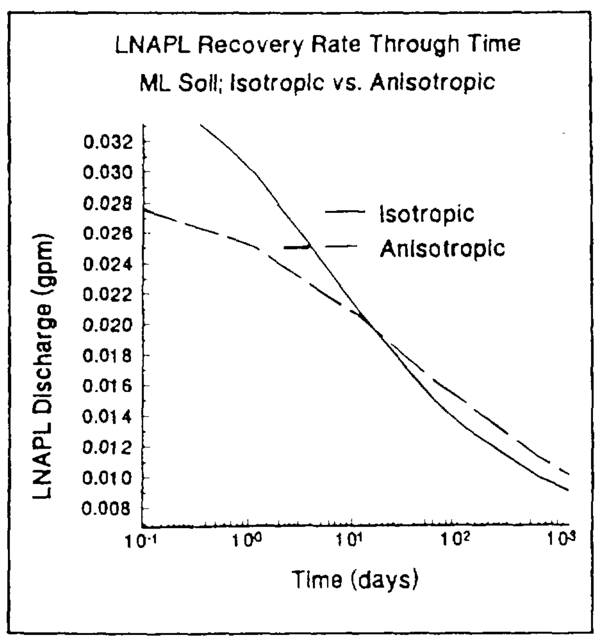


Figure 10. Predicted LNAPL recovery rates as a function of time, ML soil.

One of the critical factors limiting the area of influence of skimming wells is the development of a low hydraulic conductivity zone (with respect to the hydrocarbon phase) near the production well (Figure 11). Removal of hydrocarbon from the formation decreases hydrocarbon saturations, which in turn decreases the relative permeability (and therefore LNAPL conductivity) of the soil with respect to hydrocarbon (Equation 2b and Figure 6). A plot of relative permeability as a function of elevation and distance from the production well (Figure 11), after 3.2 years of hydrocarbon recovery, shows that the zone nearest the well (less than 1 m) has a maximum relative permeability of less than 0.1. Relative permeability can be seen to increase away from the production well.

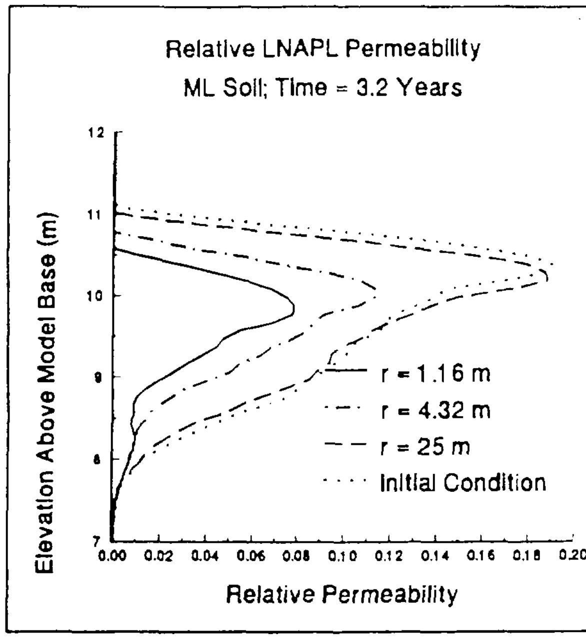


Figure 11. Relative LNAPL permeability as a function of elevation and distance from recovery well, ML soil.

Effect of Anisotropy

The effects of aquifer anisotropy were simulated by decreasing the vertical permeability by a factor of ten, while keeping the horizontal permeability the same as in the previous isotropic simulations. Thus, the initial hydrocarbon transmissivity for each of the simulations was the same as the corresponding isotropic cases, but the vertical downward movement of hydrocarbon is limited. The net effect is a reduction in the effectiveness of skimming near the extraction well, but an increase in the radius of capture and the total volume of hydrocarbon removed from the system (Table 4). Using the ML soil as an example, introducing anisotropy to the problem reduces the percentage of hydrocarbon recovered from the limited domain (within 5 m of the extraction well) from 54% to 36%, but increases the recovery from the full model domain from 7.1 to 7.8%. The effect is the same, but less marked, for the SM soil, and insignificant for the SW soil.

We hypothesize that the introduction of anisotropy increases the radial LNAPL gradient to the recovery well, as is typically seen in other anisotropic hydraulic settings. Further, because of the additional radial flux induced by the increased gradient, the hydrocarbon saturations near the well remain higher in the anisotropic soils, resulting in higher relative LNAPL permeability (this could also be caused, in part, by slower vertical drainage). The cumulative outcome of this can be seen in the plots of hydrocarbon recovery rates versus time (Figures 5, 8, 10) for the three soils. The effect of anisotropy is greatest for the fine-grained, ML, soil (Figure 10). Recovery rates are initially higher for the isotropic soil, as most of the hydrocarbon is derived from the zone near the well. With time, however, as hydrocarbon is derived from increasing distances from the skimming well, the higher horizontal gradients induced in the anisotropic case produce higher recovery rates. The cross-over in recovery rates between the isotropic and anisotropic cases occurs at the beginning of the simulation for the SM soil (Figure 8), with LNAPL recovery more effective throughout that simulation

Effect of Groundwater Drawdown

The effect of the amount of groundwater production (or drawdown) on the amount of hydrocarbon recovery was simulated by establishing a well boundary condition with 2.5, 5, 7.5, and 15 ft of groundwater drawdown and comparing the results for the SM soil. In each case, the original hydrocarbon thickness in the recovery well was 10 ft, resulting in peak hydrocarbon saturations of about 30%. In all cases, the simulation was executed in a manner to remove all hydrocarbon that entered the well, effectively keeping the oil/air interface elevation equal to the oil/water interface elevation.

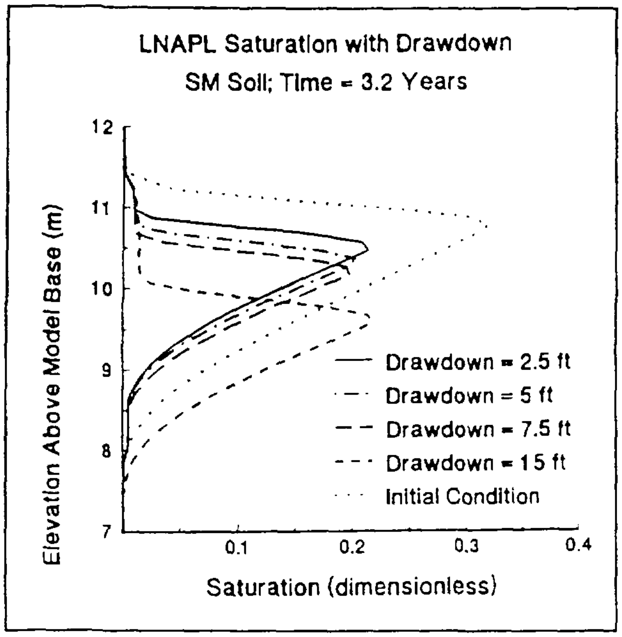


Figure 12. Effect of groundwater drawdown on LNAPL saturation 1.16 m from the recovery well after 3.2 yrs of skimming, SM soil.

Increasing the groundwater pumping rate associated with skimming acts to increase the hydraulic gradient toward the recovery well, thereby increasing recovery rates. There are several potential negative aspects of this however. First, increasing the drawdown may decrease hydrocarbon saturations near the well, thereby decreasing the hydraulic conductivity with respect to hydrocarbon (Figure 6). This may act to exaggerate the zone of reduced hydraulic conductivity near the skimming well and ultimately reduce recovery rates. Second, increasing groundwater drawdown increases the amount of impacted groundwater that must be treated before disposal. Third, increased pumping may lower the water level below the static oil/water interface, inducing hydrocarbon movement downward into previously unimpacted soils (Figure 12). If the water level subsequently rises, this hydrocarbon may become trapped as ganglia with limited mobility, acting as a long-term source of dissolved-phase hydrocarbons in ground water. Since protection of ground water resources and human health is critical, it is important that these potential negative outcomes be considered in context with site closure objectives.

The effects of increased drawdown on the hydrocarbon saturation profiles in the SM soil can be seen in figure 12. Increased drawdown does not significantly decrease peak saturations near (1.16 m) the well. Increased drawdown does, however, act to lower the profile as hydrocarbon re-distributes itself vertically. Our simulations indicate that increased drawdown markedly increases the rate of hydrocarbon recovery (Figure 13), particularly early in the skimming program. Increasing drawdown from 1.5 ft to 15 ft increases initial recovery rates from 0.04 gpm to 0.16 gpm (Figure 13).

Total volumes of recovered hydrocarbon also increase significantly with increasing groundwater pumping (Table 5). The results of our simulations did indicate that there is an optimum pumping rate (corresponding to a drawdown of 7.5 ft) to maximize recovery near the production well (limited domain area, Table 5). But increasing the drawdown continuously increased the amount of recovered hydrocarbon from the full (57.5 m radius) domain. Like the effect of anisotropy, increased groundwater drawdown might decrease the rate of recovery near the production well, but the increased drawdown enhances hydrocarbon recovery from greater distances. This points to the importance of wellfield optimization in hydrocarbon recovery system design.

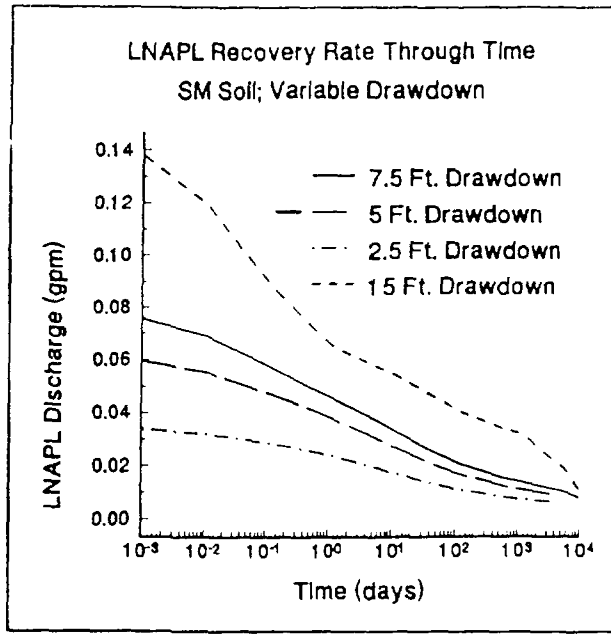


Figure 13. LNAPL recovery rate as a function of time for four different ground water drawdowns, SM soil.

Effect of Initial Hydrocarbon Thickness

Initial hydrocarbon saturations (Figure 3) are directly related to the observed thickness of hydrocarbon in a monitoring or recovery well (Farr et al, 1990; Lenhard and Parker, 1990; Huntley et al., 1994). For the SM soil used in our simulations, the peak initial hydrocarbon saturation decreased from about 30% with 10 ft of hydrocarbon in the well to less than 5% with only 2 ft of hydrocarbon in the well. Decreasing the initial thickness of hydrocarbon in the recovery well from 10 ft to 2 ft (Table 6), decreases the initial volume of hydrocarbon by a factor of 100, and decreases the volume of recovered hydrocarbon by a factor of 1000.

Table 5. Hydrocarbon Recovery as a Function of Groundwater Drawdown, SM Soil.

Groundwater Drawdown (ft)	Full Domain (57.5 m radius Area)			Limited Domain (5 m radius Area)		
	Hydrocarbon Volume (thousands of gallons)		Percent Recovery	Hydrocarbon Volume (thousands of gallons)		Percent Recovery
	Initial	After 3.2 yrs		Initial	After 3.2 yrs	
1.5	504	492	2.3	3.74	2.31	38.2
[illegible]5		486	3.5		2.1	43.8
7.5		476	5.5		2	46.3
[illegible]5		444	11.9		2.3	39.6

Vacuum-Enhanced Fluid Recovery (VEFR)

Vacuum-enhanced fluid recovery involves application of a low vacuum to fluid recovery wells. This vacuum acts to (1) increase the effective drawdown in the recovery well (i.e., gradient), thereby increasing rates of fluid movement toward the well, (2) capture hydrocarbons from the zone at and

VER

Table 6. Effect of Initial Hydrocarbon Thickness on Recovery.

Initial Hydrocarbon Thickness (ft)	Full Domain (57.5 m radius Area)			Limited Domain (5 m radius Area)		
	Hydrocarbon Volume (thousands of gallons)		Percent Recovery	Hydrocarbon Volume (thousands of gallons)		Percent Recovery
	Initial	After 3.2 yrs		Initial	After 3.2 yrs	
2	5.15	5.13	0.36	0.039	0.035	8.7
5	89	86	2.8	0.66	0.39	41
10	504	476	5.5	3.74	2.01	46

above the oil/air interface in the well, thereby removing hydrocarbon from a zone where some of the highest hydrocarbon saturations are held in the soil under a negative pressure (soil suction), and (3) increases rates of volatilization of hydrocarbon, thereby increasing mass rates of removal from the system. VEFR is, in effect, the simultaneous application of soil vapor extraction and hydrocarbon skimming using the same recovery well. MAGNAS3, unlike most multiphase modeling codes, has the capability of simulating an active air phase. It is therefore well-suited to modeling alternative remediation technologies, such as soil-vapor extraction, sparging, and VEFR. For the present research, MAGNAS3 was used to simulate the effects of VEFR on the **fluid-phase** hydrocarbon recovery. That is, we did not simulate the effects of volatilization of the hydrocarbon and removal of the vapor-phase hydrocarbons. Total volumes and rates of hydrocarbon removal (vapor + fluid) will be significantly greater in the real world than are reported here.

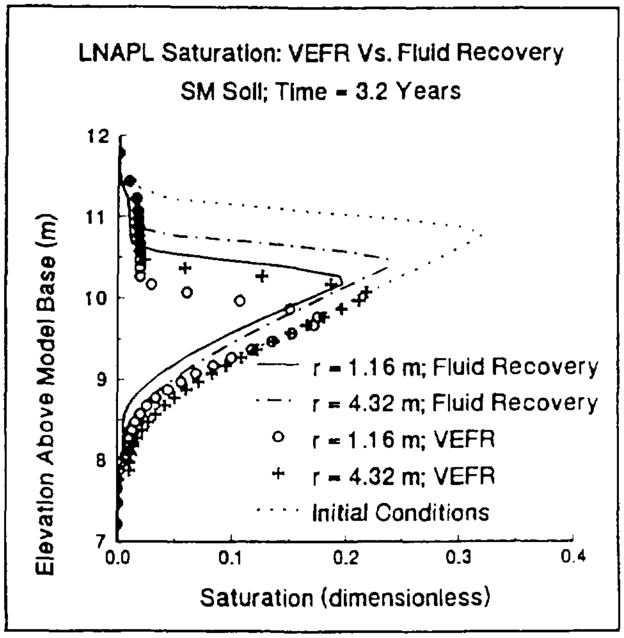


Figure 14. Comparison of the LNAPL saturation profile resulting from simple skimming and VEFR for 3.2 yrs, SM soil.

VFR

Comparison between hydrocarbon recovery rates from simple skimming and from VEFR (Figures 5, 8), shows that VEFR substantially increases rates of fluid-phase hydrocarbon recovery, particularly early in the remediation period. The effect on the saturation profiles is marked in fine-grained materials (Figure 14), but not as visible in coarser-grained materials, such as the SW soil modeled. Most notable are the sharp decrease in saturations in the upper part of the hydrocarbon profile, relative to the results of simple skimming. Like increasing the rate of drawdown, the application of a vacuum to the production well nearly doubles the percentage of hydrocarbon recovered (Table 7), but unlike increasing the drawdown, it does not encourage the downward movement of hydrocarbon into previously unimpacted soils.

Table 7. Hydrocarbon Recovery using Skimming with/ without VEFR

		Full Domain (57.5 m radius Area)			Limited Domain (5 m radius Area)		
		Hydrocarbon Volume (thousands of gallons)		Percent Recovery	Hydrocarbon Volume (thousands of gallons)		Percent Recovery
		Initial	After 3.2 yrs		Initial	After 3.2 yrs	
SW	Skimming	1,920	81	96	14.4	0.35	98
	VEFR		40	98		0.31	98
SM	Skimming	504	476	5.5	3.74	2.01	46
	VEFR		456	9.5		1.8	51

SUMMARY AND CONCLUSIONS

The relationship between LNAPL saturation and LNAPL hydraulic conductivity is critical in assessing the viability of an LNAPL recovery system. Because the relative permeability of soil toward LNAPL decreases with decreasing saturation, and because the intrinsic permeability of fine-grained soils is less than that of coarse-grained soils, free product pumping or skimming have less likelihood of success in fine-grained soil. Further, for any soil type, recovery decreases LNAPL saturation and relative permeability near the well resulting in a lower permeability region that retards recovery from greater distances.

Evaluations using MAGNAS3 (1992) showed that recovery of hydrocarbon in fine-grained soils was limited, with significant reductions in LNAPL saturation occurring only within about 10 to 15 feet of the well. Although the ML and SM soils were texturally different, total percent recoveries were similar. This suggests that silt and clay fractions can act to reduce LNAPL recovery and mobility even when the sand fraction is significant (e.g., 65% in the SM soil). Recovery of LNAPL in coarse-grained soils was predicted to be much more successful, with approximately 95% percent of the original hydrocarbon recovered through fluid pumping. However, all soils contained LNAPL saturations of concern (greater than 15% in the SW soil) after 3.2 years of remediation. Since LNAPL recovery decreases through time, hydrocarbon can persist even in the coarsest soil. Since coarse soils generally allow the greatest advective solute transport, the greatest risk may be presented by these soils even though skimming is the most successful from a volumetric recovery perspective.

Increased drawdown in the recovery well increases the total volume of hydrocarbon recovered in fine-grained soils, but causes downward migration of hydrocarbon and contamination of previously unimpacted soils. Application of a vacuum to the extraction well (VEFR) similarly increased the rate of hydrocarbon recovery, without the associated impacts to previously unimpacted soils.

The effectiveness of skimming declines markedly with decreases in the initial measured thickness of hydrocarbon in an extraction or monitoring well. This is a result of significantly smaller hydrocarbon saturations, volume, and mobility with decreasing observed thickness. However, there is no thickness exaggeration in observation wells, just an apparent volume exaggeration.